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SURGE CONTROL ON THE COACHELLA PIPE DISTRIBUTION SYSTEM

By C. S. Hale, P. W. Terrell,
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SURGE CONTROL ON THE COACHELLA PIPE DISTRIBUTION SYSTEM

By

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INTRODUCTION

In 1947 the Bureau of Reclamation undertook the construction of a pipe distribution system to carry water from the Coachella Branch of the All-American Canal to about 100,000 acres of land in the Coachella Valley. When the system was put into operation in March 1950, however, some of the laterals could not be operated satisfactorily because of severe surging (a rythmical increase and decrease in the flow past a given point) which caused extreme head variations at the farm turnouts in portions of the system. This condition not only wasted water and made proper irrigation difficult, but in some cases deliveries were insufficient for irrigation needs.

Analytical and field investigations of the surging were begun almost immediately. Later a model of part of a typical field lateral was built in the Bureau's Denver laboratories. These analytical, field, and laboratory studies led to the installation of airtight covers on the open pipe stands at each farm turnout, and these effectively controlled the surging. This monograph describes the studies that led to this solution, and gives methods by which similar systems may be designed to keep surging at a minimum.

DESCRIPTION OF IRRIGATION SYSTEM

Figure 2 shows the location of the Coachella Valley in southern California. The ground slopes from an elevation of 524 feet at the north downward to the Salton Sea, 240 feet below sea level. The temperature seldom falls below freezing, and crops are grown throughout the year. Rainfall averages about 3 inches per year, making irrigation necessary for agriculture.

Preliminary studies indicated that a low-pressure pipe system would be slightly more costly to build than an open-canal system but would permit higher delivery gradients with smaller seepage and evaporation losses and hence lower operating costs, and would entail less right-of-way encroachment through cultivated areas. Further studies indicated that a low-pressure pipe system would be materially less expensive to construct than a high-pressure system, and it was decided to construct the former. For construction purposes the system was divided into nine units (see figure 2). Figure 2 also shows the general plan for Unit 6, with the quantities of flow, the points of delivery, and the number and designation of the laterals.

The laterals are located along section and mid-section lines. Quarter-mile sublaterals are provided to serve adjoining lands, with a farm turnout to each 40 acres of land, or one and sometimes two turnouts at each quarter-mile of lateral. Open-topped box or pipe stands were constructed at each turnout point to maintain a low internal head on the pipe lines. The top of the stand was made 2 feet higher than the maximum operating water surface. A baffle or partition in the stand serves as a check at low flows to provide the head required for turnout deliveries (figure 3). Excess flows at a given turnout pass over this baffle into the downstream half of the stand, then flow through the outgoing pipe line to the next stand. This design divides 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 next stand. Turnouts from the laterals are controlled by gate or disk-type valves built integrally with a propeller-type meter.

CAUSE OF SURGING

Surging appears to be initiated by any one or all of a number of factors. These may include auto-oscillations of small amp-

FIGURE 1--Pipe stand overflowing as a result of surging.

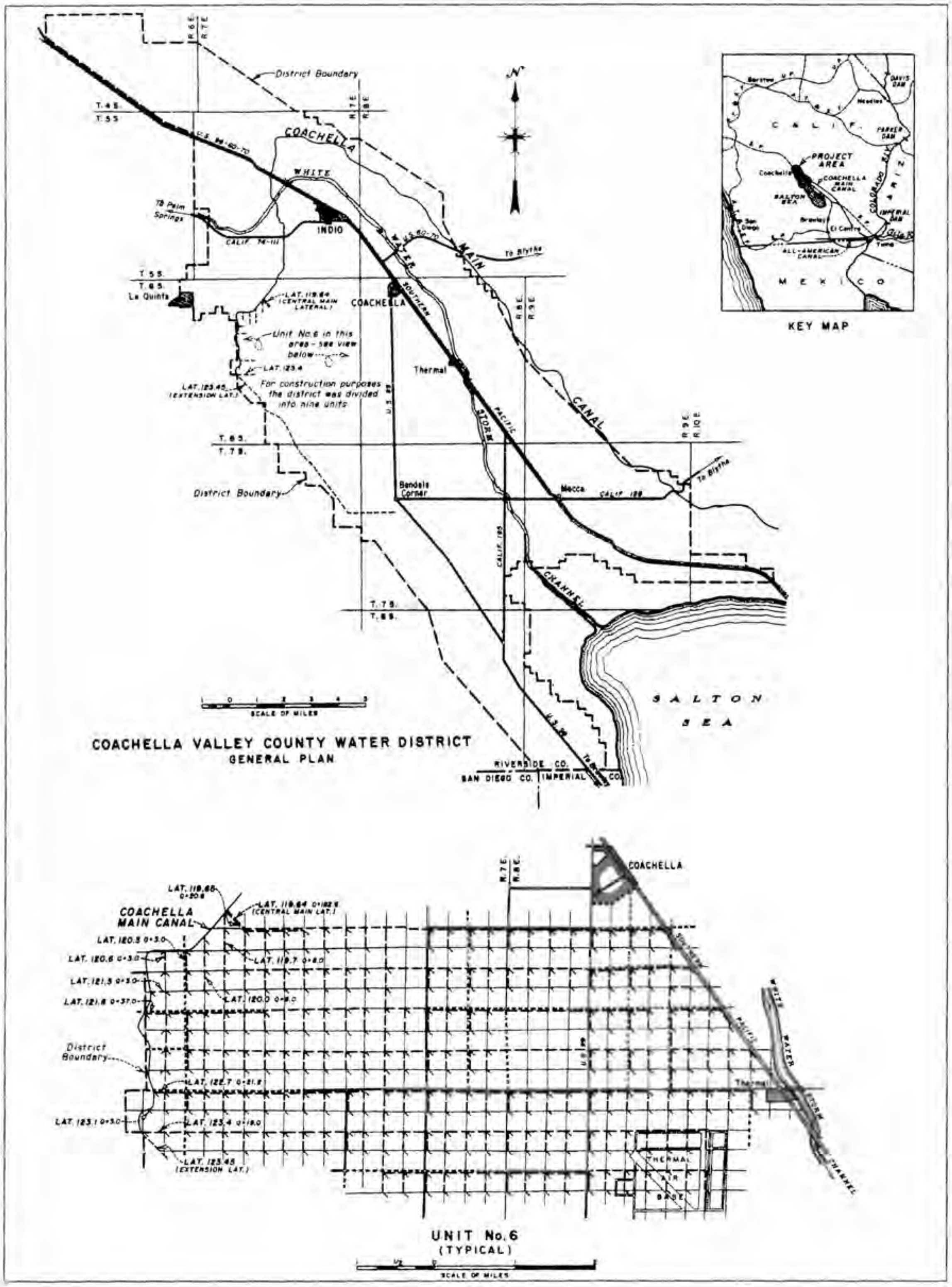


FIGURE 2--Coachella Valley County Water District. General plan and plat of Unit 6.

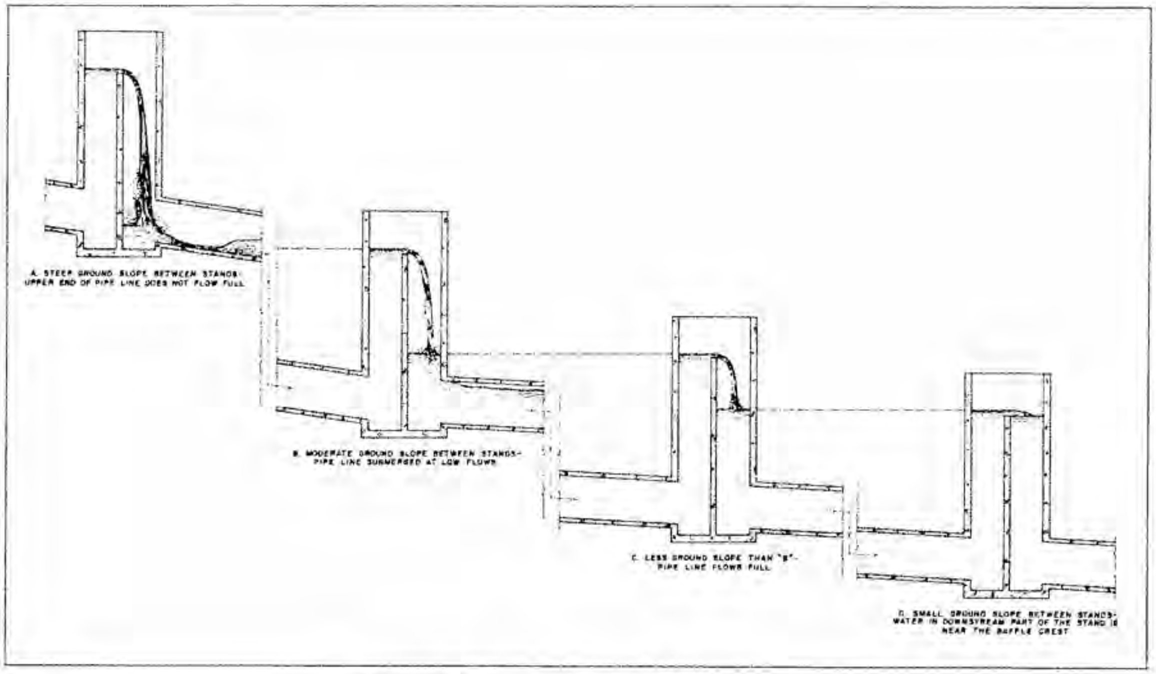


FIGURE 3--Flow conditions in pipe stands.

litude, caused by entrapment and release of air, imposed oscillations from outside sources such as by wind blowing across the tops of open pipe stands and by disturbances to flow caused by making or cutting off deliveries. Other sources probably exist. The ability of the system to amplify these initiating oscillations under certain conditions may then build them into surges of large magnitude in reaches further downstream.

The storage and release of entrapped air was found to be a source of initiating oscillations in certain pipe reaches. Water falling over the baffle in a pipe stand entrains a mass of air bubbles as it plunges into the water pool on the downstream side of the baffle. 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 against the top of the pipe. Since the pipe has a gradient in the direction of flow and the bubble floats, 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, the bubble moves upstream, and part of it discharges 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. 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 bubble formation and destruction falls into step with the oscillations and supplies the energy necessary to maintain them.

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 section lines for several miles with pipe stands at regular intervals. This equal spacing of stands and the gently sloping terrain provide a succession of pipe reaches with nearly identical natural periods. Under these conditions a small auto-oscillation originating in an upstream reach can be amplified into a surge of detrimental proportions in successive reaches.

GLOSSARY

Some of the terms used in this monograph have their origin in vibration theory. This glossary defines these terms and explains their connection with surging in pipe lines.

a. A vibrating system is created when one or more masses are subject to constraints which tend to return them to an equilibrium position or to fix the position of each with relation to the others. In a pipe distribution system the masses are the water in the pipe reaches and the constraints are the forces which tend to bring the levels in the pipe stand back to stable running levels.

b. The term degree of freedom is useful in classifying vibrating systems. The degrees of freedom of a vibrating system are the minimum number of quantities needed to describe the motions of the system. A pipe reach between open pipe stands is a one degree of freedom system because only one quantity is needed to describe its motion. This quantity can be either the departure from the normal running level in the downstream half of the upstream pipe stand or the departure from the mean velocity of the flow in the pipe reach. A system comprising two pipe reaches with the common pipe stand capped is a two degree of freedom system because two departures from normal level or two departures from mean velocity are needed to describe its motions. This system differs dynamically from two reaches with an open stand between them because the air pressure changes under the cap make the effect of movements in the lower reach felt upon the upper reach and the two reaches can no longer act independently. A system having one or more capped stands in succession has as many degrees of freedom as there are pipe reaches in the system. Such a system is a portion of the pipe line. It begins and ends at an open pipe stand but has all of the interior pipe stands capped.

c. A mode of vibration is simply the manner in which a vibration is executed. A natural mode is one which a vibrating system can execute without change of pattern if it is forcibly displaced from its equilibrium position, in a manner conforming to the pattern, and released. The number of natural modes of a vibrating system is equal to the number of degrees of freedom of the system.

d. Each natural mode has its own associated natural period.

e. The gravest mode or fundamental mode is the mode having the longest natural period. A vibrating system subjected to a sinusoidal disturbing force will execute a forced mode of vibration. This forced mode will have the same period as the disturbing force.

f. If the sinusoidal disturbing force has a period corresponding to a natural mode period the mode having this period will become predominant and the amplitude of vibration will tend to grow to a high level. This is called resonance.

g. The conditions producing resonance would tend to build up the amplitude of vibration without limit were it not for the presence of damping forces, which set a limit to the amplitudes which can be attained.

h. The amount of damping just sufficient to prevent oscillatory motion when the system is displaced from its equilibrium position and released is called critical damping. With this or greater amounts of damping, amplification by resonance cannot occur.

i. If the damping is small compared to the critical damping so that the system can oscillate freely in any of its natural modes, then amplification by resonance will always occur if the sinusoidal disturbing force has a period longer than the natural period of the system. If the disturbing force has the shorter period then amplification by resonance will occur until the ratio of the periods reaches about 1.4. Beyond this point suppression occurs.

SUMMARY AND CONCLUSIONS

Surging originates in small oscillations which may be due to a variety of causes, among which are air entrapment and release and the disturbances incident to making deliveries. These small oscillations have a period which is the same as the natural period of the reach in which they originate. In an orderly system, such as the one in the Coachella Valley, resonance occurs and gives rise to amplification. Any small surge is thereby amplified in each succeeding reach until it grows to an unmanageable magnitude. The solutions found for this trouble accomplish their purpose by either consuming the energy of the oscillation or by destroying the possibility of resonance.

General

Two factors must be present in a pipe line to cause surging. These factors are an initiating oscillation and the amplification tendency. Sources of an initiating oscillation appear to be always present. The two most potent are small oscillations driven by entrainment and release of air in the pipe line, and disturbance incident to making deliveries. However, field observations indicate the presence of other sources.

In an open system comprising a pipe line with baffled pipe stands at intervals, each pipe reach connected to a pipe stand at both ends has a natural period of oscillation. This period is a function of the pipe length and diameter and the water-surface area in the downstream half of the pipe stand at the upper end of the reach. If the natural periods of successive reaches are nearly alike, amplification will occur. Thus if a flow oscillation having a period near to the natural periods of the reaches is fed into the upper end of the line, each reach will discharge at its lower end a flow having a variation of greater amplitude than that fed into it at its upper end.

The amount of amplification is influenced by the frictional losses in the reach, which in turn depend on the amount of flow in the line. If the frictional loss is low, the amplification may be large. If the frictional forces are large, amplification may not occur. Thus surging is likely to be greatest at flows which are small compared to full capacity flow, and in pipe lines with gradients low enough to permit the pipe to remain full at no flow.

No devices have been found which will prevent air entrainment in pipe stands with a straight baffle. However, a round vertical overflow riser located in the center of a circular pipe stand is effective in reducing air entrainment. A pipe line with pipe stands of this kind will, however, amplify small surges of the proper period fed into it or created within the lateral.

Surge Control Devices

Gates.--Gates in the baffles or outlet pipe are an effective means of surge suppression, if adjusted so that no water spills over the baffle. However, a pipe line equipped with gates is cumbersome to operate.

Control of surface areas.--A pipe line can be stabilized by selecting pipe-stand sizes or adding additional water-surface area in open pipe stands to throw the various elements of the line out of synchronism. The most effective arrangement found is one in which the periods increase downstream, with successive pipe reaches having a ratio of natural periods of the order of 1.4 or more. If the line is long, such a solution adds greatly to the cost of the system.

Air vents.--Field experience with air vents has shown them to be ineffective as a means of surge control.

Covers.--Airtight covers on pipe stands control surging effectively and economically in systems with gradients low enough to permit the pipe lines to run full at low flows. A pressure relief valve and a device to relieve excessive negative pressures should be provided. (Since airtight covers exert their control through pressure changes in the air trapped under them, surging in pipe reaches laid on slopes so steep that they do not run full at low flows cannot be effectively controlled by covers because the air volume trapped under the cover is too great to be effective.)

Airtight covers produce their effect first by grouping the original pipe reaches into systems which have oscillation periods different from those of the original pipe reaches, thereby throwing the reaches out of synchronism; second by reducing the number of systems capable of resonance; and third by creating systems which do not oscillate as freely as the orginal reaches.

The application of airtight covers to a number of pipe stands in succession creates a system which behaves dynamically as a unit. This system comprises all the pipe reaches joined to the pipe stands, together with the downstream half of the open pipe stand at the upstream end of the first pipe reach and the upstream half of the pipe stand at the lower end of the last pipe reach.

Each system created by airtight covers has a number of natural modes of oscillation equal to the number of pipe reaches in the system. Each of these modes has an associated natural period for which resonance can occur. In general, resonance in the higher modes is so weak that they are of no practical significance; the mode having the longest period, or gravest mode, is of importance. Resonance in this mode is generally weaker than that of the individual pipe reaches of the system before application of the covers.

The period of the gravest mode of a system created by the use of n airtight covers in succession is approximately

$$T_n = 2\pi\sqrt{\frac{F_1}{g}\left(\frac{L_1}{A_1}+\frac{L_2}{A_2}+\ .\ .\ +\frac{L_{(n+1)}}{A_{(n+1)}}\right)}.$$

When the pipe reaches are all alike this reduces to

$$T_n = 2\pi\sqrt{\frac{(n+1)\ F_1 L_1}{A_1\ g}}.$$

This formula holds for a single reach with open stands at both ends if n is set equal to zero.

In these expressions, $L_1 \ldots L_{(n+1)}$ represents the lengths of the successive pipe reaches in the system, $A_1 \ldots A_{(n+1)}$ represent the corresponding cross sectional areas, F_1 represents the area of the horizontal cross section of the downstream half of the pipe stand at the upper end of the system, g represents the acceleration of gravity, and $\pi = 3.14159$. If the quantities $L_1 \ldots L_n$ are expressed in feet, F_1 and $A_1 \ldots A_{(n+1)}$ in square feet and g in ft/sec^2 the period T_n will be given in seconds.

The performance of a pipe line with single reaches and systems created by using airtight covers can be investigated by computing the period of each and working through the system on the assumption that an air-driven auto-oscillation can occur in the gravest mode of any reach, or system, and computing an over-all resonance factor for that part of the line downstream from the reach or system in which the oscillation is assumed to originate. The system may be considered satisfactory if none of the over-all resonance factors thus computed exceeds about 20.

The most favorable arrangement is one in which the gravest mode periods increase progressively downstream. If some features of a given line make the application of this rule awkward, then it is permissible to choose an alternative pattern, since the number of covers used on a pipe line is more important than the pattern in which they are installed. The resonance possibilities should be checked, however, in the manner described above.

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, although it represented no particular structure on any project. It consisted of a water supply system, a head box, three vertical pipe stands 20 inches in diameter, each divided into two equal vertical sections by a baffle, three 8-inch by 125-foot pipe lines connecting the stands in series, and an 8-inch return line (figure 4). Because of space limitations and for convenience in operation and viewing, the model was arranged with the head box and the stands side by side and with the pipe lines extended about 60 feet downstream, then turned back to enter the next

FIGURE 4--Overall view of headbox and stands 1, 2, and 3 in the laboratory model.

FIGURE 5--The large air bubble and entrained air in the swirling flow within the pipeline immediately downstream from headbox stand. Q = 0.37 cfs.

stand. The first 16 feet of the first line was sloped 1 inch in 16 feet to represent a typical prototype slope and the first 6 feet of this section was made of transparent plastic to permit observ ations of the flow inside the line. The rest of this line and the two other lines were sloped to provide a total drop of 3 feet each.

Water was supplied to the model by 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 pipe, then passed through a rock baffle which removed the major flow turbulences. Immediately downstream from the baffle was a motor-operated, vertically reciprocating float to be used, when desired, to produce uniform depth variations in the head box. (These forced surges or oscillations should not be confused with self-induced or auto-oscillations.) After passing the rock baffle and float the water moved to the downstream end of the box and over a rectangular baffle 20 inches wide, and entered the equivalent of the downstream half of a stand. From this half-stand the water entered the pipe line to flow to stand 1, where it filled the upstream half of the stand, passed over the baffle, and filled the downstream half of the stand sufficiently to produce flow in the pipe. From there it passed through stands 2 and 3 and then back to the main supply channel for recirculation.

The baffles were made of 1/8-inch sheet steel. Higher baffle elevations were obtained by placing extensions upon these base baffles. Sheet-metal slide gates 8 inches in diameter were placed in the base of the baffles at the elevation of the outlet pipe to permit studying the effect of gates for surge control. Windows near the bottom in the downstream section of the stands permitted observation of the water inside the stand and at the entrance of the outlet pipe.

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

It was not definitely known beforehand that the model would auto-oscillate like the field structure, but self-induced surging was noted in the model as soon as water was passed through it, even though the water was entering the head box at a constant rate. The surging was greatest at 0.37 cfs and diminished when the flow was either increased or decreased. Large quantities of air were carried into the pool in the downstream section of the pipe line (figure 5). The small bubbles collected in a large bubble in the top of the pipe which periodically became sufficiently buoyant that it moved upstream in the sloping pipe and part of it vented in the pipe stand. This cycle was in phase with the surging, as explained in the section on auto-oscillation.

MODEL AND PROTOTYPE STUDIES

Baffle Adjustment

Model studies.--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 were found to have a pronounced effect upon the surging. The greatest 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, as 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 points of successive surges 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, the self-induced surging became too small to measure. At 14 feet 11-1/4 inches the baffle in stand 1 was only 6-1/2 inches lower than the fixed head box baffle. Since the head required to cause flow through the line and over the baffle in stand 1 existed as water depth in the half-stand, 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. This suggested that in future designs 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 is discussed on page 12.

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.

Prototype studies.--Various combinations of controls on the baffle overflow were investigated in the field. These included reducing baffle crest heights for low flows and constructing deflecting baffles above the pipe stand outlet to determine the effect of varying the flow condition over the baffle and of regulating the point of impact of the falling water. None of the devices was effective.

A second baffle was constructed about 6 inches downstream from the existing baffle in two consecutive pipe stands. An opening was placed near the bottom of the second baffle to eliminate the direct fall over the baffle. This device, too, was ineffective.

Pipe Line Vents

Model studies.--The periodic build-up of the long air bubble in the outlet pipe and its venting into the stand suggested that if the pipe line were vented by other means the air could no longer cause surging. A vertical pipe one inch in diameter was placed in the plastic portion of the first pipe line. When the vent was opened, air escaped forcefully and slugs of water were thrown several feet into the air. While the surge into stand 1 and hence into stands 2 and 3 was considerably reduced by opening this vent, the small surge present was amplified.

The partial success of the vent in the plastic pipe indicated that vents between stands 1 and 2 and 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. Although there was a continual discharge of air and the occasional violent explusion of water from these vents, they had only a slight effect upon the surging. When the first vent was closed but the other two vents were left open, the average surge in stand 3 was about the same as without vents. The effect of the vents was to reduce the part the air plays in creating the surges, but 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 through the system. It was concluded that pipe line vents are impractical for prototype surge control.

Prototype studies.--The Coachella Valley Water District installed two 16-inch concrete pipe vents in each of eight successive reaches of one lateral beginning with the first pipe stand on the lateral. These two vents were located an average of 17 and 300 feet downstream from each pipe stand. The vents had only minor effect on the surging.

Gates in the Baffles

Model studies.--The 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 flow through an orifice, however, is relatively unaffected by a similar change in head, provided the orifice is operating under an appreciable head.

An attempt was made to stop the surging by utilizing this more stable flow of orifices. This was done by cutting holes, 8 inches in diameter, in the baffles at the elevation of the outlet pipes, and placing sheet-metal gates on the upstream side of the baffle. With the gates open and all the water flowing through them, no surging occurred in the system. Surging started immediately, however, if part of the water overtopped the baffles.

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 upstream and downstream from that gate. Thus, to operate a prototype lateral satisfactorily, 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 it is concluded that gates should not be used extensively for surge control. However, they may be used in limited numbers to gain partial control.

Prototype studies.--A number of 12- and 16-inch gates were installed in the laterals at selected points to eliminate the fall over the baffle at low flows and to minimize the effect of variations in incoming flow by using the gate as an orifice. Properly regulated, the gates controlled surging very effectively. However relatively minor but frequent changes in flow, caused by regulation of deliveries, variation in delivery head requirements because of adjustments in the individual farm systems, or changes in the canal water surface, made necessary a new and painstaking readjustment of all gates in the lateral. This made regulation nearly impossible except when very few gates were involved.

The Water District installed a large number of gates in Units 3 and 4. Although simple to operate when only deliveries at the downstream end of the lateral were being made because the gates could then be left open, there were many instances of unregulated surging in the laterals when the gates had to be partially closed.

It was concluded that gates, if used sparingly, are effective, but that large scale use is not considered practical because of operating difficulties.

Control Gates in Outlet Pipe Entrances

Model studies.--Tests were 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. From these experiences it was concluded that in the prototype it would be necessary to install overflow pipes from the top of the stands to the pipe lines downstream, since similar or even greater difficulty might be experienced with the gate adjustments. It was predicted that this would again permit the entrainment of air and surging would occur much the same as with the standard baffled stands.

Prototype studies.--Following completion of Lateral 119.64-2.6, it was found that surging was so severe that delivery beyond Station 65+74 was not possible. Surge control structures, consisting of a gate on the outlet pipe from the pipe stand and an overflow pipe, were constructed on the lateral at Stations 34+90, 65+74, 92+27, 105+78, 158+97, and 212+44. The purpose of the gate was to decrease the fall over the baffle by checking the water surface downstream from the baffle. This was intended to reduce the surge creating effect of the fall while providing an orifice through which the surge downstream could be reduced to a minimum. The overflow pipe provided a by-pass around the gate for water above the capacity of the partially opened gate. This modification did improve flow conditions to the extent that reasonably satisfactory deliveries could be made to Station 158+97, but surging beyond this location was virtually uncontrolled. Surging upstream from the first control structure was never completely eliminated, and surging also developed in some of the pipe stands between the control structures.

Siphons in the Baffles

Model studies. --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. 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.

These siphon baffles were installed in stands 1 and 2 and a normal flow passed through the siphons in stand 1 without difficulty, but 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 surging 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 through the 8-inch pipe into the stand, while the remainder was carried on to stand 3. Surging with an average amplitude of 0.14 foot occurred in this stand, but the flow over the baffle never entirely ceased. It is believed that greater surges associated with discontinuous flow would have occurred in succeeding stands had the system been extended. Imposed oscillations were amplified in each reach.

In addition to aiding the formation of vortices, the negative pressures in the siphon created a pronounced draw-down in the water surface at the siphon inlet. This draw-down was so great that air was drawn into the siphon even with the water near the baffle top. To relieve this draw-down and reduce the admission of air, the hoods were removed from the upstream face of the baffles. 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 siphons) and the baffle in stand 3 (without siphons) were periodically overtopped by surges. It was concluded that the siphons were not capable of controlling field surging.

Overflow Pipes in Lieu of Baffles

Prototype studies. --As a contribution to the research on the surging problem, the Concrete Conduit Company altered three pipe stands where temporary covers had been tested previously. Concrete pipes 30 inches in diameter were placed vertically in the center of the 72-inch pipe stand with connections from the 30-inch pipe to the stand inlet and the side delivery. The crest of the pipe was the same elevation as the former baffle crest. In effect, the vertical 30-inch pipe replaced the area formerly upstream from the baffle, except that the outlet portion of the stand was now much larger in surface area than the inlet portion. It was assumed that this larger area would dampen any surges coming from the inlet.

About 1.5 cfs was first turned into the lateral and the gates upstream from the overflow stands adjusted so that the incoming side of the first overflow stand was free of surges. Under these conditions very little surging could be detected in the first stand downstream from the overflow stands. These conditions also existed, however, when these three stands were operating as pipe stands. When the flow was increased to 3 cfs, surging was detected which was magnified progressively by the three stands.

The flow in the lateral was then increased to 8.1 cfs. After adjusting the gates upstream so that no detectable surging entered the first modified stand, the following readings at the inlet side of the overflow structures were measured:

Station	Surge	Period
1	1/2" to 1-1/4"	25 sec.
2	1" to 2"	20 sec.
3	1' to 2'	1 min. 3 sec.

The crest of the overflow at the third overflow station submerged at regular intervals. The variation in surge was not regular with a complete cycle of surges requiring about 11 minutes and 35 seconds. There was also some variation in the period at all of these structures. The baffle in the first stand downstream from the last modified stand also submerged periodically. Whether this submerging backed up the water in the lateral to the third modified stand or whether the surging there was repeated at the next it was not possible to determine definitely. The surging at the next stand could not be controlled by operating the gate, however, which indicated that surging was developing progressively downstream. This was also indicated by readings at the first two overflow stands.

These observations indicated that surging developed in the overflow stands, but probably at a lower rate than in the pipe stands.

Model studies.--The baffles were removed from the three pipe stands and the 8-inch inlet pipes were extended into the stands and then turned upward to rise 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 resulting larger outlet pool, together with the thinner and longer nappe from the riser pipe, resulted in much less air entrainment in the pool and much greater air separation from the water. The half-stand at the head box could not be modified, however, and the first pipe reach operated throughout these tests with 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. Observation through the windows near the bottom of the stands showed the riser pipe arrangement effectively reduced air entrainment. The nappe of the water discharging from the riser pipe 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 although with less severity than with straight baffles.

The riser pipes were extended 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. However, when the plunger was used to force oscillations into the system, these oscillations were amplified in a most striking manner.

The outlet ends of the riser pipes were returned to the elevations which produced the maximum surging and were provided with a 90^{o} V-notch on the side opposite the discharge pipe. 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 because of the flow concentration caused by the notch. This concentration of water carried some of the air deep into the pool. 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. 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 surging still occurred and that there was amplification of surges which entered the system under favorable conditions, made the inlet riser pipes unsuitable for surge control.

Studies of Air Entrainment

Model studies.--Since air entrainment and release appeared to be one of the most prevalent sources of surge-initiating oscillations in the field, tests were run to determine what might be done to prevent this trouble at its source. These tests were made on a structure of prototype size because air entrainment is believed to be relatively more important in a prototype size structure than in a model.

A wall with an outlet pipe and a control gate was placed in a large testing flume. This arrangement represented closely the downstream portion of a pipe or box stand since the tank was 8 feet deep and 4 feet wide. A separation of 2 feet between the wall and the overflow crest was provided. Figure 6 shows the flume with the wall and outlet pipe in place. Various devices, including baffles, training walls, and gratings, were tried but none proved capable of diminishing significantly the amount of air carried into the pipe. The persistence of the tendency to entrain air and carry it into the pipe is remarkable. Flow rates up to 9 cfs entrained air and carried it into the pipe even with the downstream water level almost to the crest of the baffle. It was concluded that this approach to surge control is ineffective.

Effect of Additional Water Surface Area

Prototype studies.--The period of a pipe reach depends partly on the area of the free water surface at its upper end, and it is possible to modify the period by adding to this surface. To evaluate the effect on surging of increasing this surface area, 2.5 miles of lateral were modified. Open surge stands in the form of open pipe stands were installed in the line immediately below the baffle stand

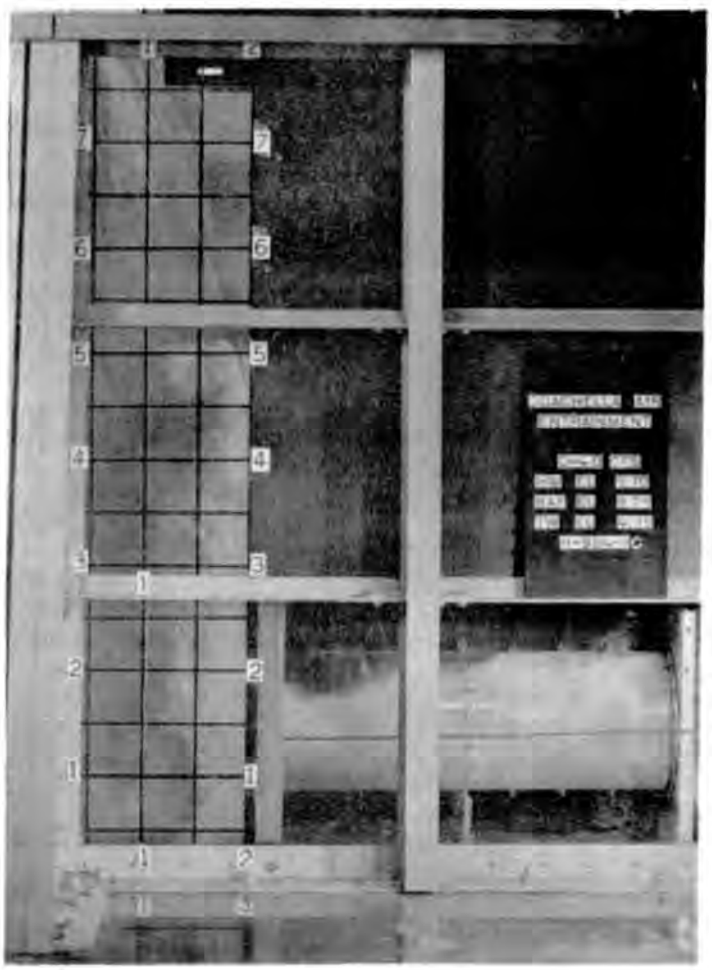


FIGURE 6--Flume with wall and outlet pipe in place.

Table 1

MODIFICATIONS OF COACHELLA LATERAL 119.64-3.1

Station	Pipe diameter feet	Pipe length feet	Stand diameter feet	Stand area ft^2	Period as built seconds	Stand area as modified ft^2	Period as modified seconds	Remarks
12+86			5.50	10.74		5.37		One-half original
	2.25	1,361			67.1		47.4	area
26+47			5.00	8.88		No change		
	2.25	1,278			59.2		59.2	
39+25			5.00	8.88		11.28		2-1.75 ft dia
	2.25	1,354			60.8		68.5	pipes added
52+79			5.00	8.88		12.86		1-2.25 ft dia
	2.00	1,265			66.2		79.6	pipe added
65+44			4.50	7.10		14.17		1-3.0 ft dia
	2.00	1,408			62.4		88.2	pipe added
79+52			4.50	7.10		No change		Gate installed
	2.00	1,184			57.2		57.2	
91+36			4.50	7.10		18.14		1-3.67 ft dia
	2.00	1,470			63.8		102.0	pipe added
106+06			4.50	7.10		19.67		1-4.0 ft dia
	1.75	1,307			68.7		114.5	pipe added
119+13			4.50	7.10		23.00		1-4.5 ft dia
	1.67	1,384			74.4		134.0	pipe added
132+97			4.00	5.62				

at the upper ends of some of the reaches. The downstream area in the first pipe stand was reduced by installing an additional baffle. These modifications were designed to increase the periods in the downstream direction. Table 1 contains data on the pipe line as built and as modified.

These modifications changed the ratio of the natural periods of the last and first reaches almost 3 to 1, but did not control the surging.

It seems probable that this method would have controlled a disturbance arising in any of the reaches in the lateral, but that the cause of the failure may be found in long period surges imposed on the lateral at its upper end. At any rate surge periods ranging from 32 to 123 seconds were recorded during the tests. It is concluded that this method of controlling surging must begin at the upper end of the entire system to be effective.

USE OF AIRTIGHT COVERS ON PIPE STANDS

Development of covers

Airtight covers on the pipe stands were first tried on the model, which was almost completely stabilized by one cover. The air pressures exerted against the cover were so great, however, as to require the installation of an air-relief valve to keep the cover from being blown off.

These findings were communicated to the field office which, using temporary plywood covers, found that nearly all stands in a line had to be covered to stabilize it, rather than every third stand as indicated by the model.

A mathematical analysis was next carried out for a system with one cover. This analysis showed that the time required to extend this analysis to systems with two or three covers would be prohibitive, and electric analog devices were used instead. These were found to be highly effective.

These studies indicate that covers are effective in suppressing surge creation because covers create systems with different natural periods, greatly reduce the number of oscillating systems in which resonance can occur, and because systems with covered stands do not resonate as freely as those with open stands. Oscillations may continue to occur, but surging will not cause trouble if the control established is sufficient to prevent complete cessation of flow over the baffles.

Test of Temporary Air-tight Covers in Field

The temporary covers consisted of two layers of 3/4-inch plywood in which a rubber flapped air valve was installed to relieve air pressure inside the stand, but to prevent entry of air into the stand. The edges of the cover sealed airtight by seating on a rubber strip. The space around the edge was filled with tar. While the laboratory tests indicated that not more than two stands in succession would need to be covered, and that at least one stand between pairs of covered stands could be left open, in the field it was found that covers had to be placed on virtually every stand before adequate deliveries could be made in the lower reaches of the lateral. It was also found that the effect of covers on existing surges was largely passive, and that to be effective covers must be installed on the stands where the surges originate.

Negative pressures frequently built up beneath the cover of such magnitude as to materially reduce the side deliveries. In at least one case the pressure became so low that an adjoining 10-inch line meter ran backwards periodically even though water was continually flowing in the lateral. To permit deliveries under these conditions a valved vacuum relief pipe which extended into the water upstream from the baffle was installed in certain covers. The maximum amount of vacuum was controlled by the depth that the end of the pipe penetrated the water surface. It was found that the proper depth of penetration was about 6 inches below water surface. This provided sufficient vacuum to control the surge downstream without materially reducing the normal adjoining delivery.

The maximum flow attained in the covered system was about 15 cfs as compared to the designed capacity of 23.2 cfs. With the lateral in operation additional flows of as much as 6 cfs have been turned into the lateral almost instantaneously without ill effect. This lateral was successfully operated for several weeks with the temporary covers installed.

Permanent Air-tight Covers in Field

As initially constructed, the permanent covers conformed in detail to that shown on figures 7 and 8. Eleven covers were installed on Lateral 119.64 which included each pipe stand from Station 253+75 to Station 412+77. This installation provided a completely covered pipe line from the 60-inch quarter-bend stand at Station 267+34, which was not covered, to the 42-inch pipe stand at Station 426+29, a distance of 3 miles. To eliminate the effect of surging upstream from the first covered pipe stand at Station 253+75, two 16-inch gate valves were installed in the baffle of the box stand at Station 240+80. Vacuum relief pipes were installed in all covers.

The lateral has been successfully operated with flows up to 11 second feet at the initial covered pipe stand at Station 253+75, about 50 percent of capacity. It has also been reaffirmed that installation of the vacuum relief pipe at a depth of 6 inches below the baffle is effective in maintaining the desired side delivery while controlling the surges.

The lateral has operated with covers thus far successfully. The concrete covers have been more effective in controlling surges than were the temporary covers first installed, presumably because they are more nearly airtight. However, the covers alone developed some operating difficulties, necessitating the installation of pressure relief and vacuum control devices. A relatively high vacuum occurs in the stands when the lateral is first placed in service. This is caused by the initial surging in the lateral and is soon dissipated by friction. A vacuum of about six inches of water is maintained in the stands by a bubbler pipe and a pressure relief valve. Should the water level in the stand rise, the pressure relief valve opens and exhausts the air. Then, when the water recedes, the bubbler pipe acts as a brake or snubber, slowly returning the water level to normal. Should the rise in water level exceed a certain minimum, however, the bubbler pipe develops a sort of vacuum lock. The vacuum relief valve has been found necessary to restore control in such a situation (where a surge forces nearly all the air from under the cover) by readmitting air to the stand. The vacuum relief is a simple ball valve, which is weighted with a short piece of welding rod. The valve is adjusted to maintain a vacuum of about six inches by cutting the rod.

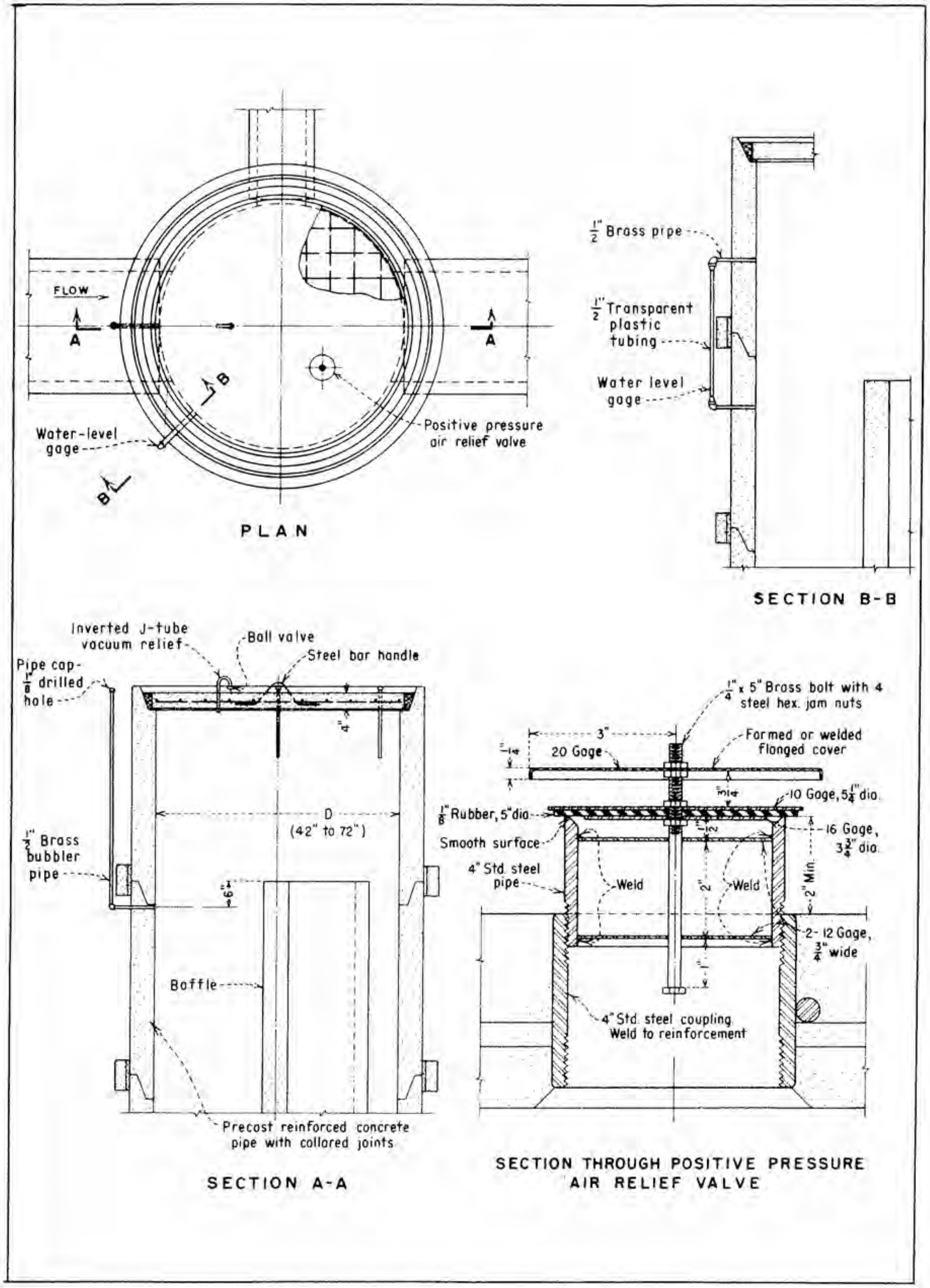
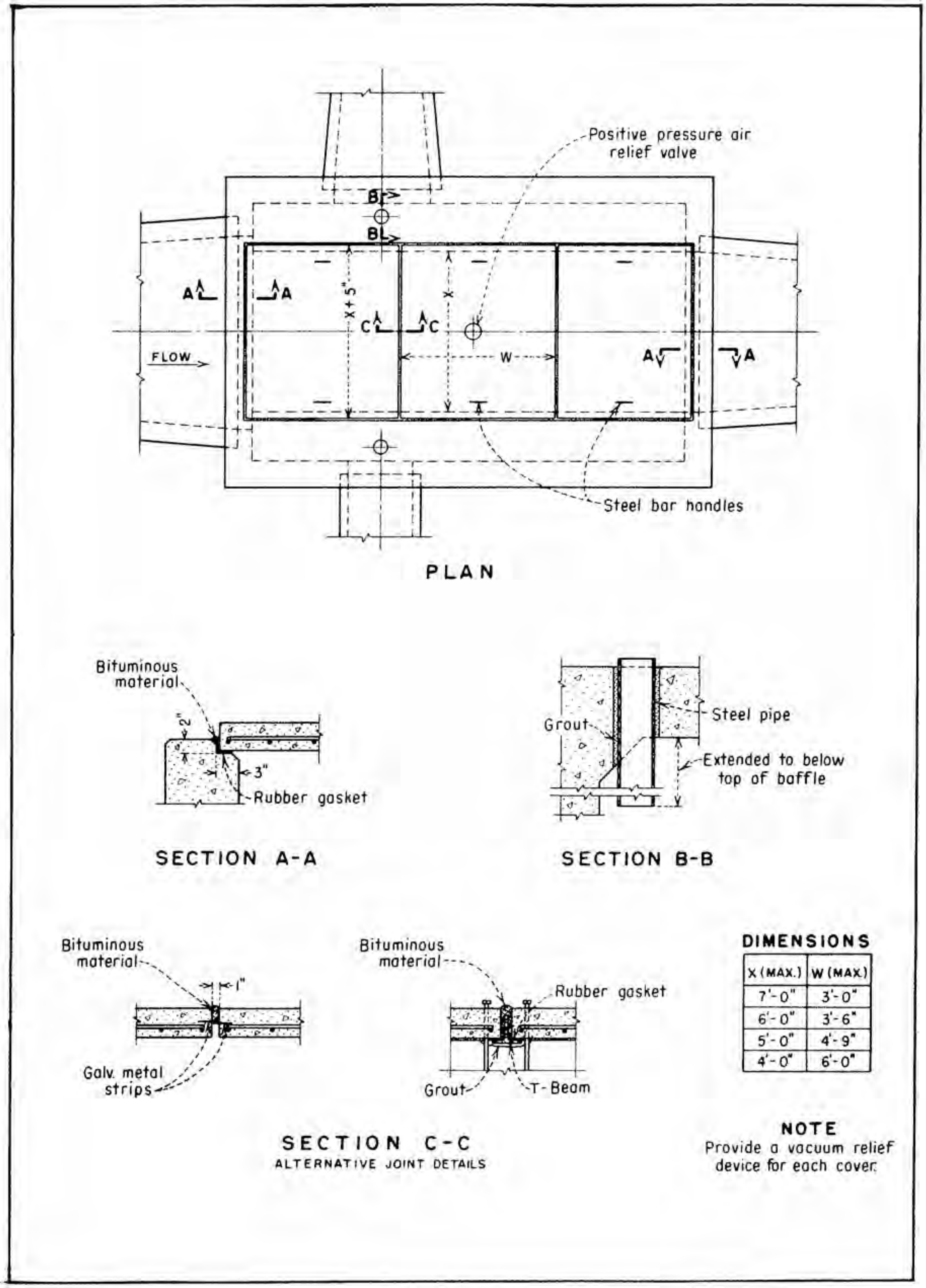


FIGURE 7--Permanent precast concrete cover for pipe stands.



X (MAX.)	W (MAX.)
7'-0"	3'-0"
6'-0"	3'-6"
5'-0"	4'-9"
4'-0"	6'-0"

FIGURE 8--Permanent precast concrete cover for box stands.

One cover on the lateral was deliberately raised by opening sufficient air release valves on the covers upstream until a surge was created sufficient to float the cover. The cover immediately settled in place and seated well so that a vacuum was created in the stand.

The concrete covers shown in figure 7 have been modified from the original design. A valve-controlled vacuum relief pipe was originally led outside the pipe stand. This was cumbersome, and the bubbler pipe was installed. The bubbler pipe maintained a vacuum of about six inches under normal conditions. When a heavy surge entered the stand, however, the water surface rose nearly to the cover, causing high vacuum as has been previously described, completely preventing delivery to farm turnouts. Air had to be readmitted to the stand to lower the water surface enough to permit deliveries. The inverted J-tube in the cover allows this because the ball valve is adjusted to open at a vacuum greater than six inches, and to reclose when the vacuum is reduced to that point.

No means of determining the level of water in the stand was provided in the original design. The ditch rider was forced to rely entirely on maintaining a continual record of flow in the lateral. Errors could accumulate toward the end of the run and more water than desired was often in the line. Installing the transparent water gages on the pipe stands eliminated this source of error.

Covers for the head boxes were made as detailed on figure 8, with vacuum control devices and level gages similar to the pipe stands.

Considerable concern has also been expressed that the covers would be objectionable when repairs were being made to the side delivery structure, since the side outlet could not be plugged from the inside of the stand without removing the covers. After the permanent covers had been installed, one 10-inch line meter head was removed for repairs. Because the air valve and vacuum relief valve were closed, the vacuum under the lid held the water in the stand so that very little pumping was required. Thus the airtight covers would appear to offer no problem as far as maintenance is concerned.

Analytical Investigations of System with Covered Stands

The analytical studies described in the following paragraphs reveal the amplifying possibilities of a pipe reach between box stands when a variation of flow is fed into it at approximately its own natural frequency. Formulas for natural frequency and amplification are given, and the case of two reaches with a capped stand between them is also treated. The damping effect of pipe line friction is accounted for.

Notation.

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

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

$$C_1 = \frac{2gh_o}{V_oL},$$

$$C_2 = \frac{Ag}{F_1L},$$

$$C_3 = \frac{2gh_o}{V_oF_1L},$$

$$C_4 = \frac{2\pi}{T_1F_1},$$

F_1, F_2 = horizontal cross-sectional areas of the downstream parts of pipe stands (see figures 9 and 11),

g = the acceleration of gravity (ft/sec^2),

h = the friction loss in a pipe reach of length L at the velocity V (ft/sec),

h_a = the accelerating head,

h_o = the value of h at the mean velocity V_o,

H_o = the absolute pressure of the air in a capped box stand, expressed in equivalent feet of water,

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

$$K_1 = \frac{C_3 \left(C_2 - \frac{4\pi^2}{T_o^2} \right) + C_4 \frac{2\pi}{T_o} C_1}{\frac{4\pi^2}{T_o^2} C_1^2 + \left(C_2 - \frac{4\pi^2}{T_o^2} \right)^2},$$

$$K_2 = \frac{-C_3 \frac{2\pi}{T_o} C_1 + C_4 \left(C_2 - \frac{4\pi^2}{T_o^2} \right)}{\frac{4\pi^2}{T_o^2} C_1^2 + \left(C_2 - \frac{4\pi^2}{T_o^2} \right)^2}$$

L, L_1, L_2 = pipe lengths in feet (see figures 7 and 9),

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

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

n_2 and n_3 = departures from the running level on the upstream sides of pipe stands in feet (see figure 11),

q = the amplitude of the flow oscillation entering a reach (ft^3/sec),

Q = the flow entering a reach (ft^3/sec),

Q_o = the mean value of the flow entering a reach,

S = the volume of air in a capped pipe stand (ft^3),

T_o = the period of oscillation for flow variation entering a reach in seconds (see figures 9 and 11),

T_1 = the natural period of a single reach between open pipe stands,

T_n = the natural period of a system such as is shown in figure 9 or figure 11,

v = the amplitude of variation of velocity in a pipe reach (ft/sec),

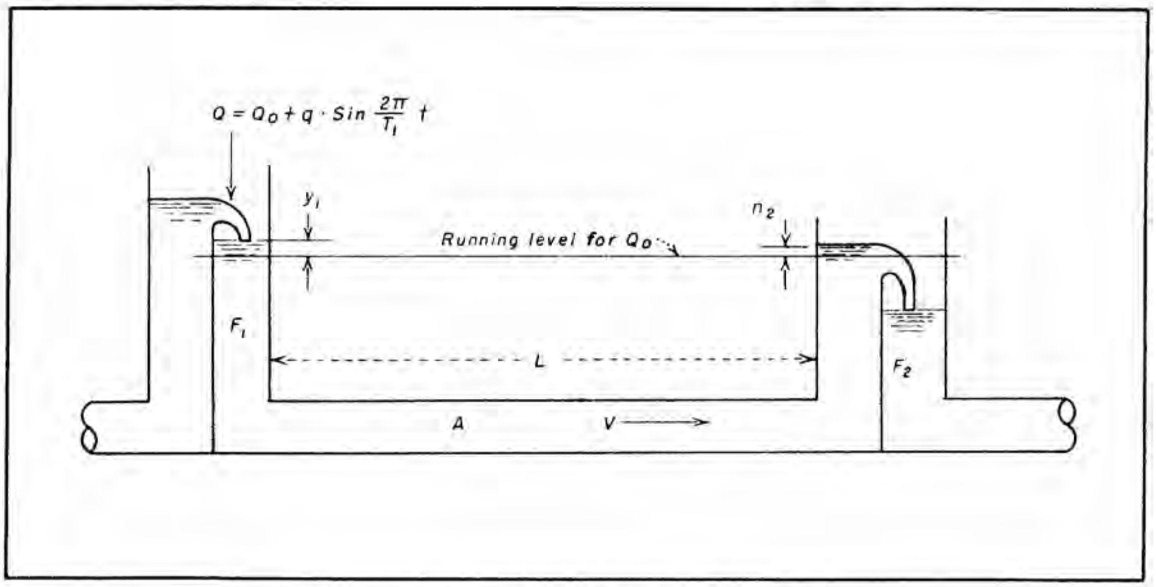


FIGURE 9--The single reach of pipe between two stands.

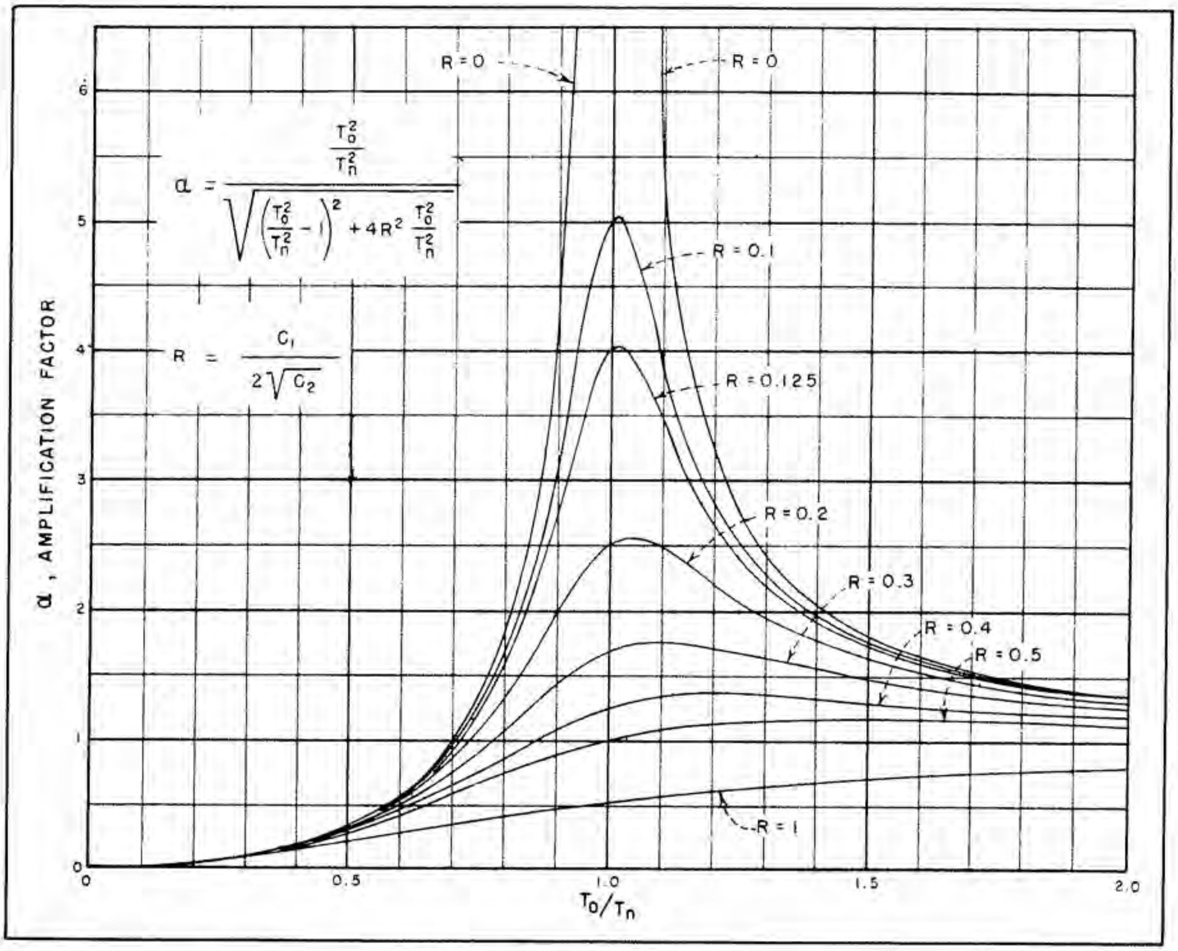


FIGURE 10--Resonance factors.

V = the velocity in a pipe reach (ft/sec),

V_o = the average velocity in a pipe reach,

y_1 = the departure from the running level on the downstream side of a box stand in feet (see figures 9 and 11), and

α = amplification factor

$$= \sqrt{\left(1 + K_2\frac{2\pi F_1}{T_o}\right)^2 + \left(K_1\frac{2\pi F_1}{T_o}\right)^2},$$

$\ll$ = much less than.

The Single Reach of Pipe Between Box Stands.--The performance of a system such as that shown in figure 9 can be specified 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

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

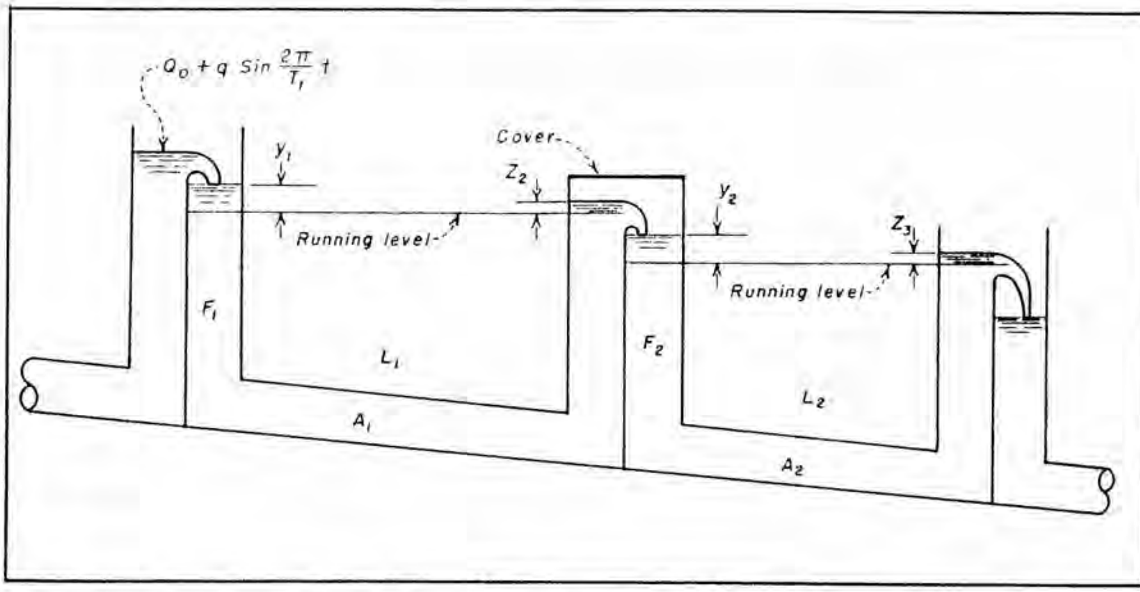


FIGURE 11--System with two pipe reaches--common stand covered.

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

$$V = V_o + v \quad \ldots\ldots\ldots\ldots \quad (3)$$

where V_o represents the mean velocity over a period of time and v represents a deviation from the mean. Then if the friction loss is

$$h = MV^2 \quad \ldots\ldots\ldots\ldots \quad (4)$$

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,

$$h = MV_o^2 + 2MV_o v, \text{ for } \frac{v}{V_o} \ll 1.$$

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

$$h = h_o + \frac{2h_o}{V_o} v, \text{ for } \frac{v}{V_o} \ll 1 \quad \ldots\ldots \quad (5)$$

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

$$F_1 \frac{dy_1}{dt} + Av = q \sin \frac{2\pi}{T_o} t \quad \ldots\ldots \quad (6)$$

and

$$\frac{L}{g} \frac{dv}{dt} = y_1 - \frac{2h_o}{V_o} v \quad \ldots\ldots\ldots\ldots \quad (7)$$

By differentiation and substitution

$$\frac{d^2 y_1}{dt^2} + \frac{2gh_o}{V_o L} \frac{dy_1}{dt} + \frac{Ag}{F_1 L} y_1 =$$

$$\frac{2gh_o}{V_o} \frac{q}{F_1 L} \sin \frac{2\pi}{T_o} t + \frac{2\pi}{T_o} \frac{q}{F_1} \cos \frac{2\pi}{T_o} t \quad (8)$$

The particular integral of this equation permits an evaluation of the amplification factor and represents the conditions which will be present in the reach after the initial oscillations have died out.

In order to state the particular integral concisely, it will be expedient to rewrite equation (8) in the form shown below. The C quantities are constants which may be evaluated by comparing the two forms of the equation.

$$\frac{d^2y_1}{dt^2} + C_1 \frac{dy_1}{dt} C_2 y_1 = C_3 q \text{Sin}\left(\frac{2\pi}{T_o} t \right) + C_4 q \text{Cos}\left(\frac{2\pi}{T_o} t \right) \quad \ldots\ldots\ldots\ldots (9)$$

The particular integral is, then,

$$Y_1 = K_1 q \text{Sin}\left(\frac{2\pi}{T_o} t \right) + K_2 q \text{Cos}\left(\frac{2\pi}{T_o} t \right) \quad \ldots\ldots\ldots\ldots (10)$$

where

$$K_1 = \frac{C_3 \left(C_2 - \frac{4\pi^2}{T_o^2} \right) + C_4 \frac{2\pi}{T_o} C_1}{\frac{4\pi^2}{T_o^2} C_1^2 + \left(C_2 - \frac{4\pi^2}{T_o^2} \right)^2} \quad \ldots (11)$$

and

$$K_2 = \frac{-C_3 \frac{2\pi}{T_o} C_1 + C_4 \left(C_2 - \frac{4\pi^2}{T_o^2} \right)}{\frac{4\pi^2}{T_o^2} C_1^2 + \left(C_2 - \frac{4\pi^2}{T_o^2} \right)^2} \quad \ldots (12)$$

The amplitude of oscillation of y_1 is

$$y_m = q\sqrt{K_1^2 + K_2^2} \quad \ldots\ldots\ldots (13)$$

The velocity variation from the mean may be obtained from the continuity condition as

$$v = \frac{q}{A} \text{Sin}\left(\frac{2\pi}{T_o} t \right) - \frac{F_1}{A} \frac{dy_1}{dt} \quad \ldots\ldots (14)$$

from which, by substitution

$$v = \left(\frac{1}{A} + K_2 \frac{2\pi}{T_o} \frac{F_1}{A} \right) q \text{ Sin}\left(\frac{2\pi}{T_o} t \right) - \left(K_1 \frac{2\pi}{T_o} \frac{F_1}{A} \right) q \text{ Cos}\left(\frac{2\pi}{T_o} t \right) \quad \ldots\ldots (15)$$

For purposes of simplicity this may be expressed by

$$v = M_1 q \text{ Sin}\left(\frac{2\pi}{T_o} \right) t - M_2 q \text{ Cos}\left(\frac{2\pi}{T_o} t \right) \quad \ldots (16)$$

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

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

The Period of a Single Reach.--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.

$$\frac{d^2y_1}{dt^2} + C_2 y_1 = 0 \quad \ldots\ldots\ldots\ldots (18)$$

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

$$y_1 = B_n \text{ Sin}\sqrt{C_2}\,(t + \beta) \quad \ldots\ldots (19)$$

Where B_n and β 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

$$T_n = 2\pi\sqrt{\frac{F_1 L}{Ag}} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \quad (20)$$

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 α will 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 with a period close to the natural period of the reach. The significance of an α 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 T_n/T_1 and the ratio $\frac{C}{2\sqrt{C_2}}$. The latter expresses the relation between the actual damping and the critical damping. The significance of 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 α greater than unity can never be obtained if $\frac{C}{2\sqrt{C_2}} > 1$. These relations are often expressed in graphical form by charts of the type shown in figure 10.

From this study it may be concluded that if a flow, oscillating about a mean 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. Amplification factors up to six have been found under field conditions. It should be noted that the effect of varying n_2, the effect of a turnout at the lower end of the reach , and the force of the water falling into the cushion at the upstream end of the reach have all been investigated and found to be of minor significance.

Effect of Covered Pipe Stands.--Installation of an airtight cover alters the dynamic characteristic of the two adjacent reaches because the air volume trapped under the cover is subject to pressure changes which modify the action of both reaches. The new system is shown diagrammatically in figure 11. Because of the greater complexity of this system, friction will be neglected in the interest of simplification.

The isothermal relation for the air under the cover is:

$$SH = S_o H_o \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad (21)$$

For small changes

$$\frac{dH}{dS} = -\frac{S_o H_o}{S^2} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad (22)$$

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

$$\frac{dH}{dS} = -\frac{H_o}{S_o} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad (23)$$

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

$$Q_o + q \sin\left(\frac{2\pi}{T_o} t\right) - F_1 \frac{dy_1}{dt} - A_1 V_1 = 0 \quad . \; . \; . \quad (24)$$

and

$$A_1 V_1 - F_2 \frac{dy_2}{dt} - A_2 V_2 = 0 \quad . \; . \; . \; . \; . \quad (25)$$

The dynamic equations are

$$\frac{L_1}{g}\frac{dV_1}{dt} = y_1 - \frac{H_oF_2}{S_o}y_2 \quad . . . . . . (26)$$

and

$$\frac{L_2}{g}\frac{dV_2}{dt} = \left(1 + \frac{H_oF_2}{S_o}\right)y_2 \quad . . . . . . (27)$$

The required solution of these equations is

$$V_1 = \left[A_2 - \frac{a^2F_2L_2S_o}{g(S_o + F_2H_o)}\right] \frac{Kq \operatorname{Sin} at}{A_1\,(a^4 - Ba^2 + A_2K)} + \frac{Q_o}{A_1} \quad . . . (28)$$

$$V_2 = \frac{Kq \operatorname{Sin} at}{a^4 - Ba^2 + A_2K} + \frac{Q_o}{A_2} \quad . . . . . . (29)$$

$$y_1 = \left[\frac{A_2L_1}{A_1g} - \frac{a^2F_2L_1L_2S_o}{A_1g^2(S_o + F_2H_o)} + \frac{F_2H_oL_2}{g\,(S_o + F_2H_o)}\right] \frac{aKq \operatorname{Cos} at}{a^4 - Ba^2 + A_2K} \quad . (30)$$

$$y_2 = \frac{aL_2S_o}{g(S_o + F_2H_o)}\,\frac{Kq \operatorname{Cos} at}{(a^4 - Ba^2 + A_2K)} \quad (31)$$

where

$$a = \frac{2\pi}{T_o},\; K = \frac{A_1g^2(S_o + F_2H_o)}{F_1F_2L_1L_2S_o},$$

$$B = \frac{K}{g}\left[\frac{A_2F_1L_1}{A_1} + F_2L_2\frac{(S_o + F_1H_o)}{(S_o + F_2H_o)}\right] \quad (32)$$

These equations show that the response of the system also occurs at the imposed period T_o as in the previous case. There are now two resonance frequencies, however, where there was only one before. These frequencies occur at values of a which are roots of the equation

$$a^4 - Ba^2 + A_2K = 0 \quad . . . . (33)$$

The four roots of this equation lead only to two frequencies.

To summarize, the system consisting of two pipe reaches with the intermediate pipe stand capped 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 capped stands arranged to form two systems of the type analysed. It was found possible to propagate surges through these reaches. Some advantage should accrue from capping alternate stands, however, even though an auto-oscillation may be present and fall into step with one of the natural frequencies of the first system so that the amplification occurs in the second and later system. This is because there will be only half as many amplifications as when no covers were used. Capped stand systems may also be helpful if used to alter the frequencies of certain parts of a lateral which without covers would have nearly the same frequencies and correspondingly high amplification factors. This will not provide a complete cure since the surge will be propagated through the capped stand system in some amount so that amplification in succeeding reaches would be possible. There should be a definite improvement, however, because the number of amplifications has been reduced by one. Also, the amplification factor for the capped stand system should be less than for the individual reaches because it is out of synchronism with the imposed frequency.

A system with three pipe reaches with the two intermediate pipe stands capped would provide a three-degree of freedom system with three corresponding natural mode frequencies. However, the gravest mode period for the two-cap system should be longer than the gravest mode for the one-cap system which in turn 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 covers were applied.

To illustrate how these relations might be used, consider a system of six pipe reaches.

With a certain partial flow a resonance 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 capped to form three one-cap systems, the amplification factor might still be four, but now the over-all amplification might be about $4^2 = 16$, which is much better. Suppose now that covers are applied to provide an arrangement with an individual reach feeding into a system of two reaches with the intermediate stand capped, and which feeds in turn into a system of three reaches with the two intermediate stands capped. A surge originating anywhere on this system would not be amplified much because the possibilities of resonance have been largely destroyed. This is in accordance with the field experience that better operating conditions are obtained as more covers are applied. In field installations an air-relief valve and a bubbler pipe are provided. The air-relief valve will let air out of the pipe stand, but will not let it in. The bubbler pipe has one end open to the atmosphere and the other end is immersed about a half foot beneath the water surface on the upstream side of the baffle. These devices and the J-tube through the cover control and maintain the vacuum under the cover and effectively minimize surges that may develop.

Electric Analog Studies of Systems with Covered Stands

Description of the Analog.--A hydraulic system with three pipe reaches and two covered pipe stands is shown in figure 12. The analogous electrical circuit is shown in figure 13. In these figures,

- A = area of a pipe cross section (ft^2),
- C = capacity of a condenser (farads),
- E = electrical pressure (volts),
- F = area of the cross section of the downstream half of a pipe stand (ft^2),
- g = acceleration of gravity (ft/sec^2),
- H = the equivalent, in feet of water, of the absolute air pressure in a covered pipe stand (ft),
- I = current (amperes),
- i = amplitude of sinusoidal component of the current (amperes),
- L = length of pipe reach (ft),
- Q = flow of water (ft^3/sec),
- q = amplitude of the sinusoidal component of flow (ft^3/sec),
- R = electrical resistance (ohms),
- S = volume of air in a capped pipe stand (ft^3),
- T = a prototype period (seconds),
- t = prototype time (seconds),
- V = velocity of flow (ft/sec),
- y = departure from normal running level of a water surface in the downstream side of a pipe stand (ft),
- J = inductance (Henrys), and
- n = analog time (seconds).

The following equations are written for a hydraulic system with three pipe reaches and two capped pipe stands, such as is shown

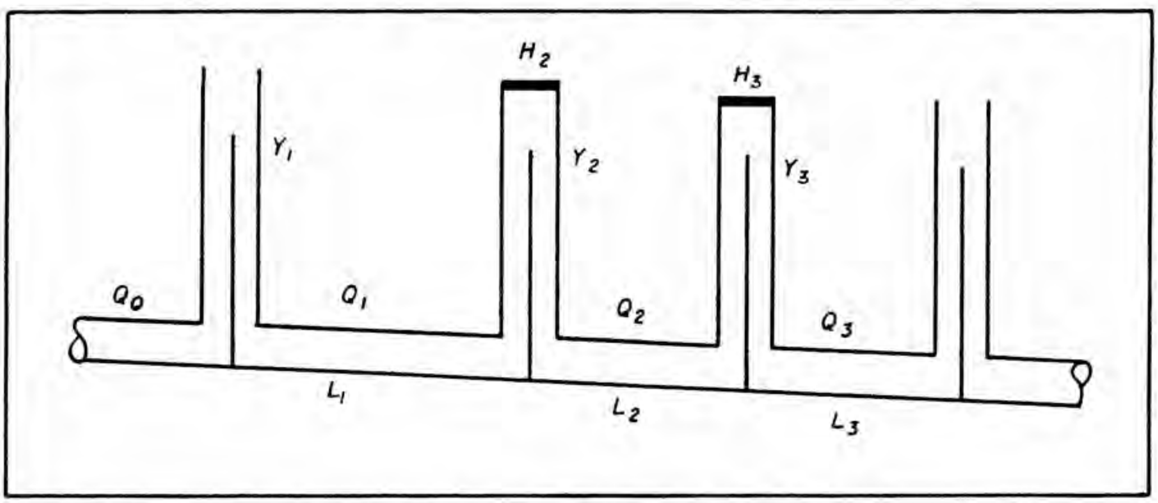


FIGURE 12--System with three pipe reaches--two pipe stands covered.

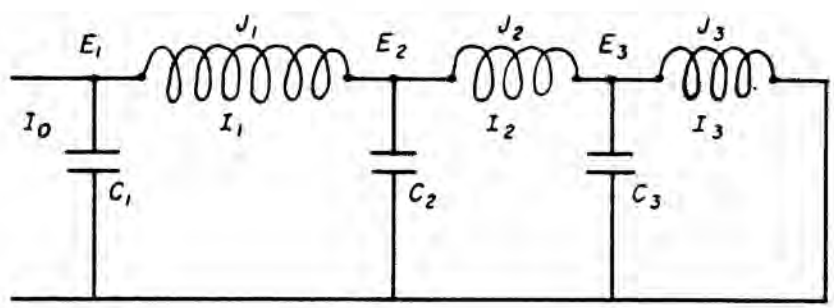


FIGURE 13--Analogous electrical circuit for system with three pipe reaches--two pipe stands covered.

in figure 12, and for the analogous electrical circuit, figure 13. The continuity equations for the hydraulic system are

$$\left.\begin{aligned} &Q_o + q_o \operatorname{Sin}\left(\frac{2\pi}{T_o} t\right) \\ &\qquad - F_1 \frac{dy_1}{dt} - Q_1 = 0 \\ &Q_1 - F_2 \frac{dy_2}{dt} - Q_2 = 0 \\ &Q_2 - F_3 \frac{dy_3}{dt} - Q_3 = 0 \end{aligned}\right\} \quad . \; . \; . \; . \; . \; (34)$$

The dynamic equations for the three pipe reaches are

$$\left.\begin{aligned} &\frac{L_1}{A_1 g}\frac{dQ_1}{dt} = y_1 + \frac{H_2F_2}{S_2} y_2 = 0 \\ &\frac{L_2}{A_2 g}\frac{dQ_2}{dt} - \left(1 + \frac{H_2F_2}{S_2}\right) y_2 \\ &\qquad\qquad + \frac{H_3F_3}{S_3} y_3 = 0 \\ &\frac{L_3}{A_3 g}\frac{dQ_3}{dt} - \left(1 + \frac{H_3F_3}{S_3}\right) y_3 = 0 \end{aligned}\right\} \quad . \; . \; . \; (35)$$

The electrical continuity equations are

$$\left.\begin{aligned} &I_o + i \operatorname{Sin} bn - C_1 \frac{dE_1}{dn} - I_1 = 0 \\ &I_1 - C_2 \frac{dE_2}{dn} - I_2 = 0 \\ &I_2 - C_3 \frac{dE_3}{dn} - I_3 = 0 \end{aligned}\right\} \quad (36)$$

where the quantities i and b in the term i Sin bn will be chosen to represent, in the analog, the term $q_o \operatorname{Sin}\left(\frac{2\pi}{T_o} t\right)$ in the hydraulic system.

The electrical dynamic equations are

$$\left.\begin{aligned} &E_1 - J_1 \frac{dI_1}{dn} - E_2 = 0 \\ &E_2 - J_2 \frac{dI_2}{dn} - E_3 = 0 \\ &E_3 - J_3 \frac{dI_3}{dn} = 0 \end{aligned}\right\} \quad . \; . \; . \; . \; . \; . \; . \; . \; (37)$$

Corresponding quantities in the hydraulic and electrical systems will be as follows:

Hydraulic	Electrical
Quantity of flow	Current
Water surface elevation	Voltage
Inertia	Inductance
Storage	Capacity
Frictional drag	Resistance
Time	Time

Before an analog can be set up, it is 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 are found by this process.

The correlation equations adopted were

$$\left.\begin{aligned} y_1 &= E_1 \\ y_2 &= \frac{S_2}{H_2F_2} E_2 \\ y_3 &= \frac{S_3}{H_3F_3} E_3 \\ Q &= 1{,}000\ I \\ t &= 1{,}040{,}000\ n \end{aligned}\right\} \quad \ldots\ldots\ldots\ (38)$$

The process of transformation may be illustrated as follows:

Transform the equation

$$Q_o + q_o \operatorname{Sin}\left(\frac{2\pi}{T_o} t\right) - F_1 \frac{dy_1}{dt} - Q_1 = 0.$$

By substitution from the correlation equations,

$$1{,}000\ I_o + 1{,}000\ i_o \operatorname{Sin} \frac{2\pi}{T_o} (10)^6 (1.04) n -$$

$$F_1 \frac{dE_1}{(1.04)(10)^6\ dn} - 1{,}000\ I_1 = 0$$

or, after reduction,

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

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

$$1{,}000\ I_1 - F_2 \frac{S_2}{H_2F_2} \frac{dE_2}{(1.04)\ (10)^6\ dn} -$$

$$1{,}000\ I_2 = 0,$$

or

$$I_1 - \frac{F_2S_2}{H_2F_2(10)^9(1.04)} \frac{dE_2}{dn} - I_2 = 0,$$

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,

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

Comparing this equation with the corresponding electrical equation, which is the first of 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 $\frac{H_3F_3}{S_3}$ 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 $\frac{H_3F_3}{S_3}$ and $1 + \frac{H_3F_3}{S_3}$.

The quantities used in the analog were

$A = 3.1416\ ft^2$ (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,
$S_2 = S_3 = S_4 = 121.4\ ft^3$

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

and $J_1 = J_2 = J_3 = J_4 = 0.0125$ Henrys.

The resistance of these coils was about 3.5 ohms.

This analog will work at around 10,000 cycles per second. This frequency is high enough so that air-core coils can be used. This provides an accurate analog but recordings must be made from an oscilloscope. A second analog, to be described later, was made with iron-core coils in order to work at frequencies low enough to permit recording with an oscillograph. This permitted simultaneous recording of all the pertinent quantities. These two analogs will be referred to hereafter as the high-frequency and low-frequency analogs. The iron-core coils used in the low-frequency analog did not permit determinations as accurate as those obtained with the air-core coils of the high-frequency analog. The high-frequency analog was used to check the computed frequencies and the low-frequency analog was used where simultaneous recordings were required. The natural periods obtained with the high-frequency analog are shown in table 2.

Table 2

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

Open stands	Capped 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

Table 2 shows 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 capped stands.

Low-Frequency Analog.--This analog was computed to work in the neighborhood of 50 cycles per second, permitting the sequence of starting oscillations to be recorded on an oscillograph. Equations (34), (35), (36), and (37) were used with the correlation equations

$$\left.\begin{aligned} E_1 &= y_1 \\ E_2 &= \frac{H_2F_2}{S_2} y_2 \\ E_3 &= \frac{H_3F_3}{S_3} y_3 \\ Q &= 1,000\, I \\ t &= 3,320\, n \end{aligned}\right\} \quad \ldots\ldots\ldots\ldots (39)$$

These correlation equations lead to

$C_1 - 2.58(10)^{-6}$ farads,
$C_2 = C_3 = C_4 = (0.86)(10)^{-6}$ farads, and
$J_1 = J_2 = J_3 = J_4 = 3.93$ Henrys.

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

$$R_C = \sqrt{\frac{4J}{C}},$$

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

Operating Results with the Low-Frequency Analog.--The observed resonance points are shown in table 3.

Table 3

NATURAL PERIODS OF THE HYDRAULIC SYSTEM AS OBTAINED FROM THE LOW FREQUENCY ANALOG

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

Again, for one open stand and three capped stands there should have been four frequencies, but, as before, only three were found.

Computed Periods.--The computed periods are as shown in table 4.

Table 4

COMPUTED PERIODS

Open stands	Capped 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		

These equations are computed directly from equations 1 and 2

Resonance Spectra.--The curves of figures 14, 15, and 16 show four resonance spectra obtained by feeding the output of the low frequency analog into an oscillograph recorder. A diagram of each of the four spectra shows the system represented. The oscillatory component of flow fed into the system is shown at the bottom of the sheet in each case. The imposed period is shown by the scale near the center of each figure. The periods are shown for a prototype structure with 5-foot-diameter pipe stands and with 1,320 feet of 2-foot-diameter pipe. Since the scale of all the q records is the same (within about 4 percent), the resonance factors can be obtained by comparing the band widths of the q records. For example,

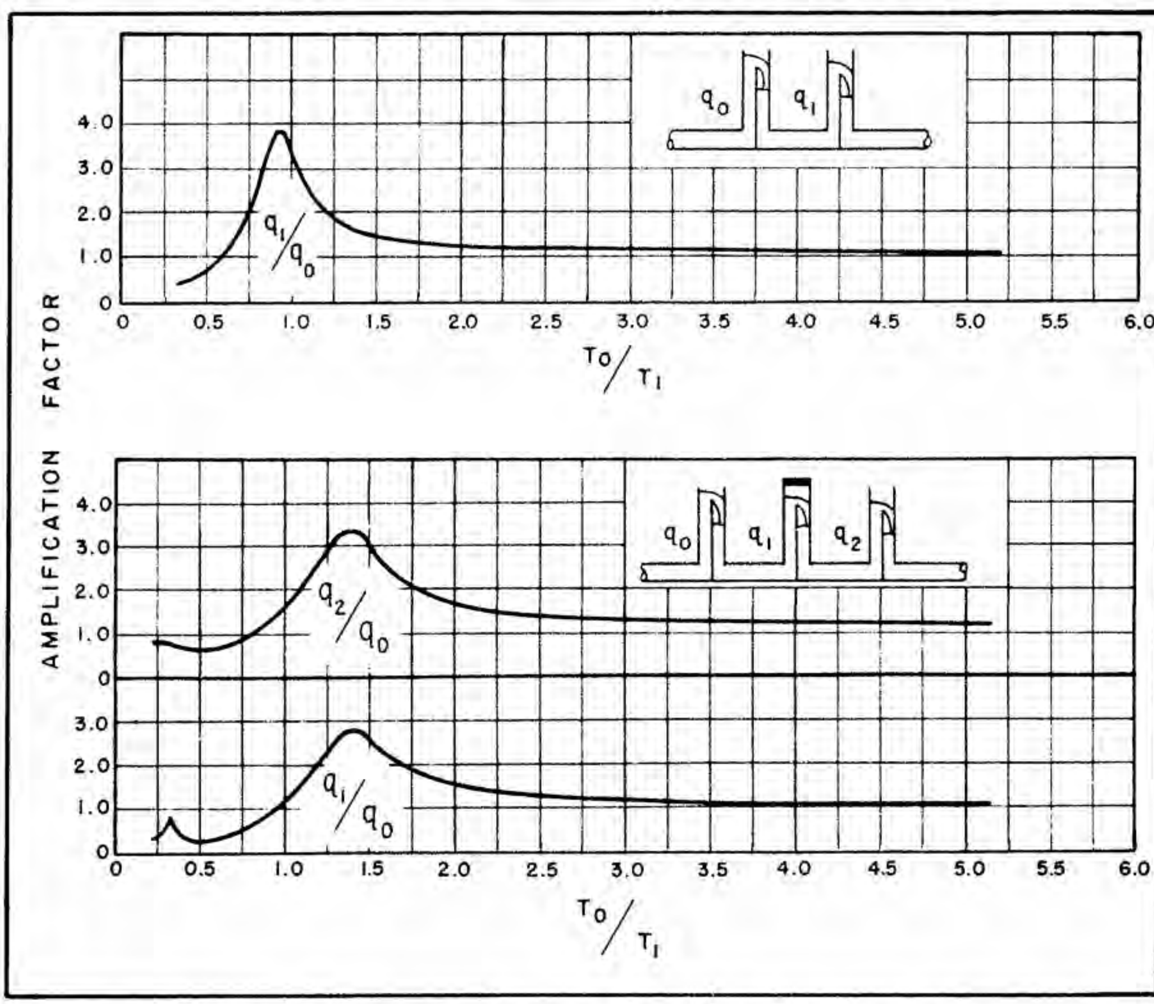


FIGURE 14--Resonance spectra for system with single pipe reach and for system with two pipe reaches--common stand covered.

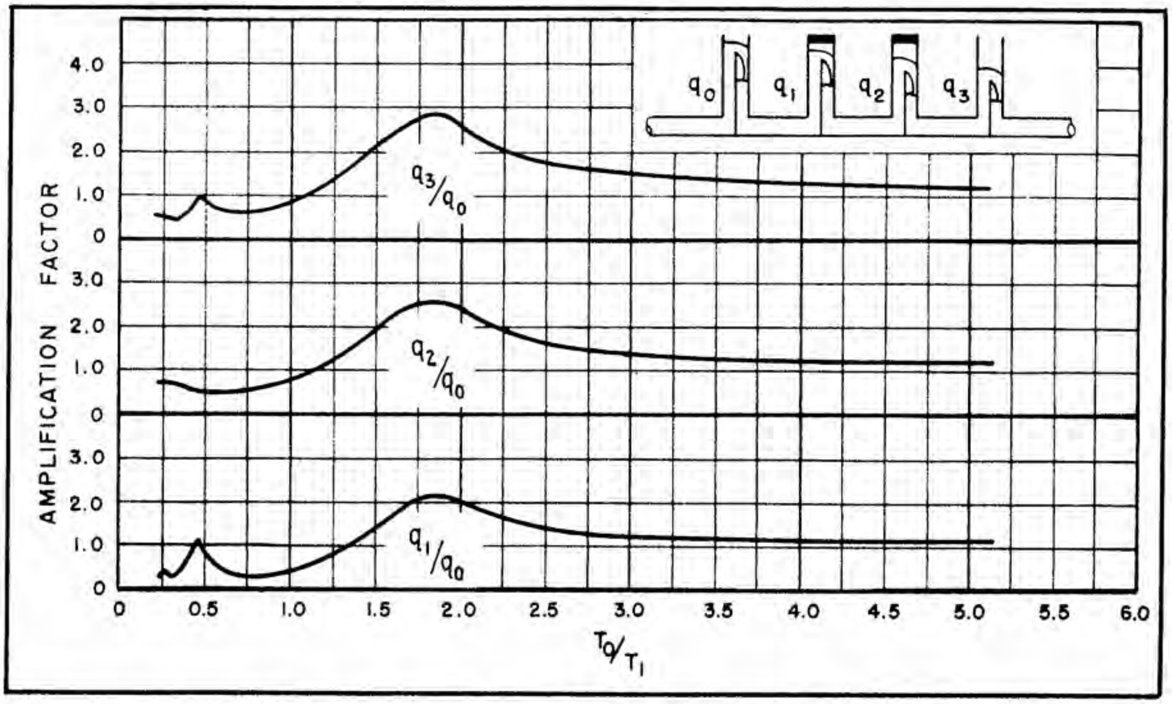


FIGURE 15--Resonance spectra for system with three pipe reaches--two stands covered.

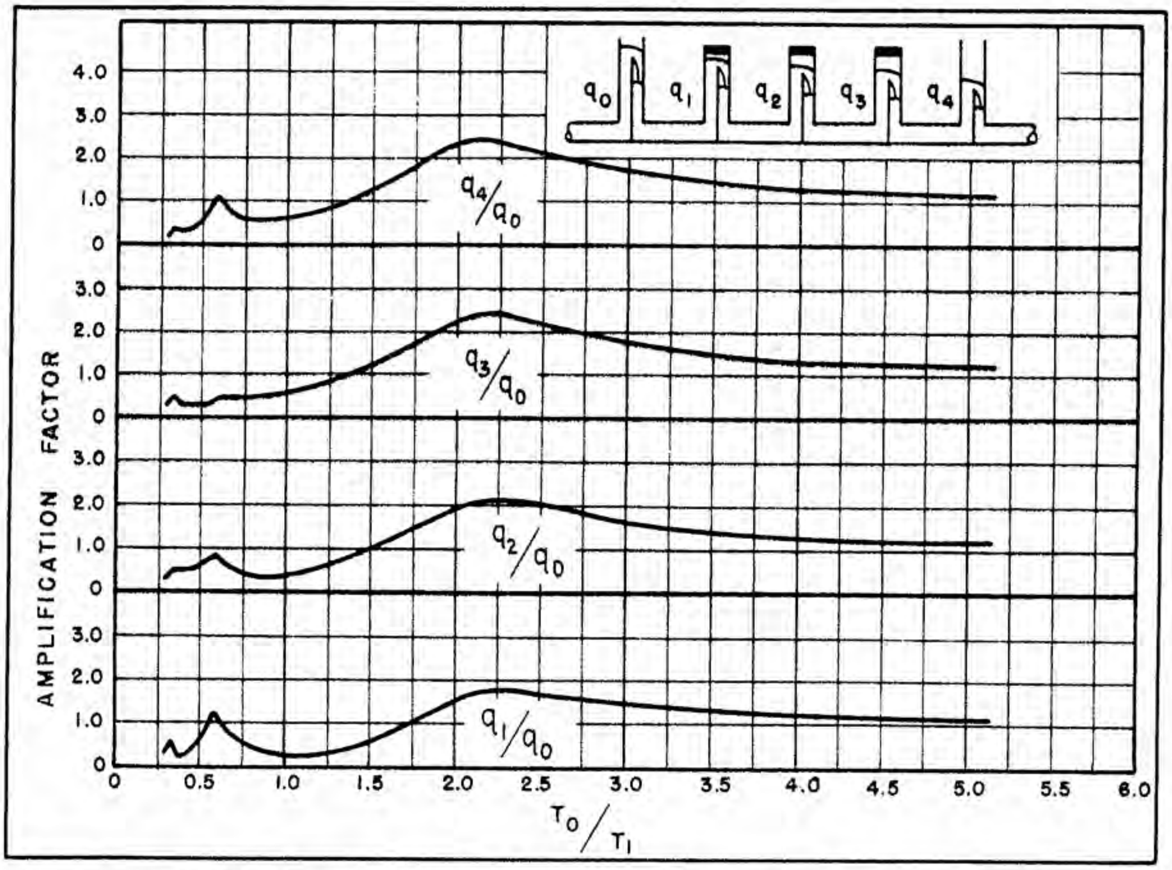


FIGURE 16--Resonance spectra for system with four pipe reaches--three stands covered.

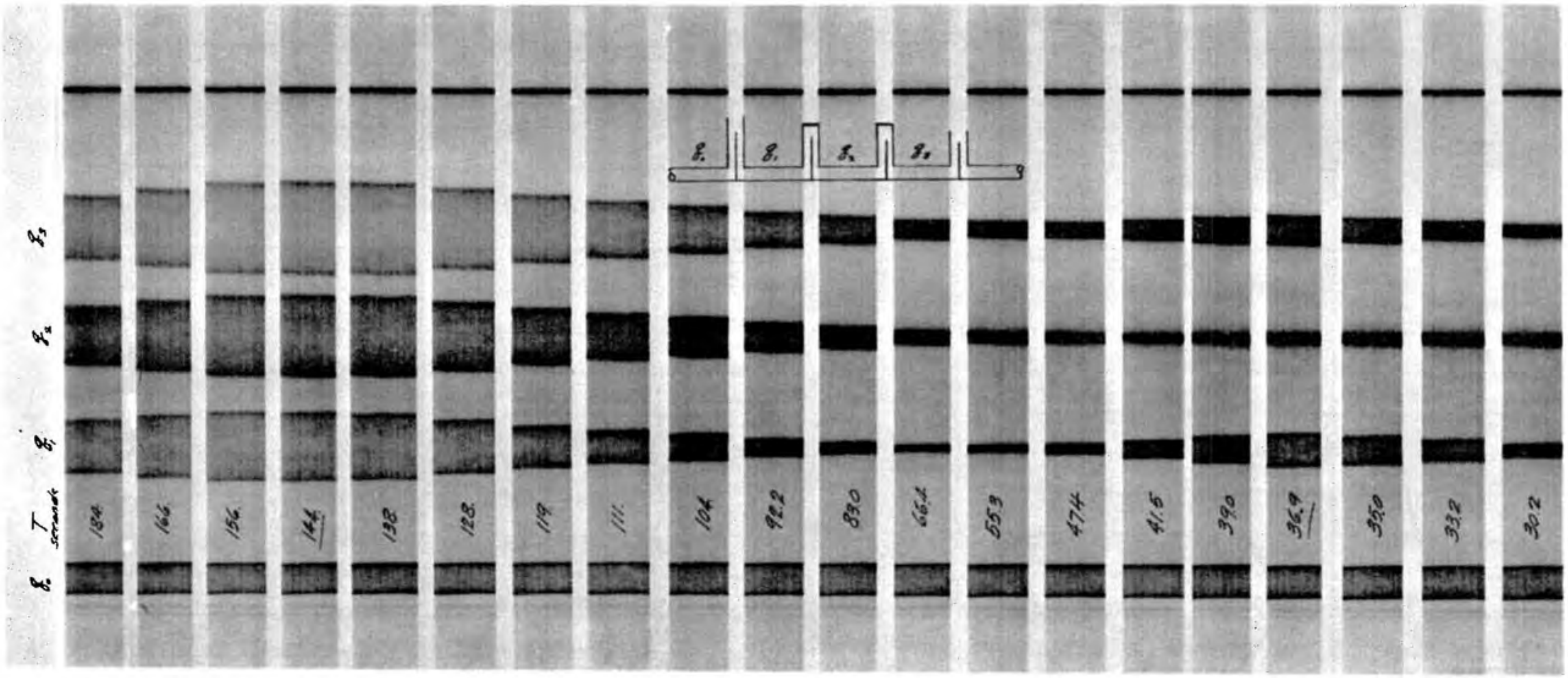


FIGURE 17--A portion of the oscillograph record of the electric analog of a system with three pipe reaches--two pipe stands covered. The bands in the record are the traces from which the curves in figure 15 were plotted. Note that the time scales of these two corresponding figures read in opposite directions.

Table 5

COMPARISON OF NATURAL MODE PERIODS AS OBTAINED FROM COMPUTATIONS, FROM ANALOG OPERATION AND FROM EXPERIMENTS ON THE LABORATORY MODEL

Open stands	Capped stands	Natural periods--seconds Computed*	Analog**		Lab model**	
1	0	21.9	21.6		21.5	
1	1	30.1, 7.3	31.5,	7.5	35.0,	7.0
1	2	36.5, 9.0, 5.2	40.3,	10.0	42.0,	9.2

* Undamped natural period
** Points of maximum resonance

on the system with no covers the resonance factor at a period of 66.4 seconds is about 4. It has been noted that there is some variation in observed periods in different runs with the low-frequency analog. This is believed to be due to the use of iron-core coils.

Checks and Correlations.--In order to obtain comparative figures for periods, computations were made for the hydraulic model and the analog was modified to represent the model by changing the condensers. Tests were run on the analog and the laboratory model was operated with zero, one, and two covers under various imposed periods obtained by operation of the head box plunger motor. A comparison of the results obtained is shown in table 5.

Computation of Resonance Factors.--When a pipe line is in the design stage, it is important to know whether the proposed arrangement would tend to surge and, if so, how covers could be used to control it. If a line has been built and is known to surge then it becomes important to determine how to place covers to stabilize the line.

The amplification estimates required can be best made by using the formulas of conclusion (n) together with the curves of figure 10. This is an approximate method

Table 6

PIPE DIMENSIONS AND RELATED QUANTITIES

Pipe reach	Pipe length feet	Pipe diameter feet	Pipe stand diameter feet	A	F_1*	Period--sec $T = 2\pi\sqrt{\frac{F_1 L}{Ag}}$
			5.0		18.59	
1	1,320	2.50		4.91		78.3
			4.5		14.97	
2	1,325	2.00		3.14		88.0
			4.5		14.97	
3	1,321	2.00		3.14		87.9
			4.5		14.97	
4	1,318	2.00		3.14		87.8
			4.0		11.73	
5	1,319	1.67		2.19		93.1
			4.0		11.73	
6	1,322	1.67		2.19		93.2
			4.0		--	

* This figure allows for a baffle wall 5 inches thick.

and neglects the possibilities of resonances in the higher modes, but it has the advantages of simplicity and generality and appears to be adequate for these purposes. The use of the curve for R = 0.125 in figure 10 is recommended for these computations as illustrated in the following applications. Although the possibility of resonance to an auto-oscillation arising in the first reach only is illustrated, a similar computation should be carried through for an auto-oscillation occurring in any subsequent reach if the natural periods vary enough to warrant it. An auto-oscillation will have the period of the reach in which it originates.

Example.--Consider the case of a lateral with the six pipe reaches whose dimensions are given in table 6. The natural period of each reach is shown in the last column. The periods (last column in table 6) are close enough together to cause trouble. Computations of the over-all resonance factor for an auto-oscillation occurring in the first reach are shown in table 7.

Table 7

RESONANCE COMPUTATION FOR LINE WITH NO COVERS

Pipe reach	$\frac{T_o}{T_n}$	α
1	--	1.0
2	0.889	2.7
3	0.891	2.7
4	0.892	2.7
5	0.841	2.0
6	0.840	2.0
		78.7

The amplification factors α are read from figure 8 using the curve for R = 0.125. This curve shows a peak amplification factor of about 4, which is reasonable for pipes of this size. A closer evaluation is probably unwarranted since the friction loss depends on the flow. The value of α used for Reach 1 in this computation is taken as unity since the disturbance is assumed to originate in this reach. The amplification factors for the individual reaches are shown in the last column. The figure at the bottom of this column is the product of the individual amplification factors and represents the number of times the amplitude of the original disturbance would be amplified at the end of the line. Note that we do not know the amplitude of the original disturbance and cannot, therefore, compute the actual final amplitude. This will be the usual situation when designs are being prepared. Field observation, however, indicated that the line will probably operate satisfactorily if the over-all amplification does not exceed 20. This arrangement does exceed that factor and it would therefore be wise to take steps to reduce the over-all amplification.

Suppose a cover is placed on alternate pipe stands. This will group the pipe reaches into three systems with two reaches in each. The computation is shown in table 8. This line should now be satisfactory for any disturbance originating in the line. If, however, this line is a lateral supplied from a longer line having an oscillation with a period of about 125.5 seconds, then the resonance factor at the end of the line would be (4.0) (4.0) (3.5) = 56 and a troublesome surge would be a distinct possibility.

Table 8

RESONANCE COMPUTATION FOR LINE WITH ALTERNATE PIPE STANDS COVERED

Pipe reaches	F_1	$\left(\frac{L_1}{A_1} + \frac{L_2}{A_2}\right)$	$T_n = 2\pi\sqrt{\frac{F_1}{g}\left(\frac{L_1}{A_1} + \frac{L_2}{A_2}\right)}$	$\frac{125.5}{T_n}$	α
1-2	18.59	690.8	125.5	1.000	-
3-4	14.97	840.4	124.2	1.010	4.0
5-6	11.73	1205.9	131.7	0.953	3.5
					14.0

The effect of placing a cover on all of the pipe stands except the first and last may be estimated as follows. All of the pipe reaches are now grouped into one system whose period is

$$Tn = 2\pi\sqrt{\frac{F_1}{g}\left(\frac{L_1}{A_1}+\frac{L_2}{A_2}+\frac{L_3}{A_3}+\frac{L_4}{A_4}+\frac{L_5}{A_5}+\frac{L_6}{A_6}\right)},$$

$$t = 6.2832\sqrt{\frac{(18.59)\ (2737.2)}{32.2}},$$

$$t = 249.8 \text{ seconds.}$$

The line should now be strongly stable. An air-driven auto-oscillation occurring in this system would be of small amplitude and could not be amplified. Even though a period of about 249.8 seconds were imposed on it through its connection to the main line, there would still be no trouble since a resonance factor of about 4 or less is all that could be expected.

It will be noted that no attempt has been made to completely eliminate all oscillations, which is probably impossible. In all cases the purpose has been to apply covers in such a way as to reduce the amplitude of possible oscillations to a point where they will not interfere with the operation of the line. If these amplitudes are kept within bounds so that flow over the baffles does not cease, this purpose will be accomplished.

DIVISION OF WORK AND ACKNOWLEDGMENTS

C. S. Hale as Construction Engineer of the Coachella Division was in charge of all work done in the field. P. W. Terrell directed the technical phases of the design work. R. E. Glover was in charge of analytical computation of periods and with the development of analog devices. W. P. Simmons, Jr. performed the experimental work in the laboratory. Kenneth Fienup contributed to much of the early progress toward solution of the problem by making analyses of conditions in pipe lines known to surge. G. G. Balmer contributed the analysis of the system with one cover, made computations of periods for comparative purposes, and assisted with the design of the analogs. C. S. Daum developed the low-frequency analog which produced the resonance spectra for systems with one, two, and three covers. The Concrete Conduit Company of Colton, California, modified one of the Coachella laterals at its own expense to assist with the investigations. This work helped materially to clarify certain aspects of the surging phenomena.

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