AN EXPERIMENTAL VERIFICATION OF THE THEORY FOR CLASSICAL WATER HAMMER

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In Partial Fulfillment
of the Requirements for the Degree
Masters of Science in Engineering

by
Thomas Walter Godfrey

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ABSTRACT

Title: AN EXPERIMENTAL VERIFICATION OF THE THEORY FOR CLASSICAL WATER HAMMER.

This thesis is an investigation of the water hammer effect caused by sudden closure of a valve on a closed conduit, when the pressure of the negative wave is allowed to drop to absolute zero thereby causing a break in the water column.

Study of the water hammer pressure waves was carried out by the use of a cathode ray oscilloscope and a brass pressure cell with SR-4 strain gauges mounted on it.

The conclusions drawn from this investigation were: 1) The water column does not hold together when the pressure drops to absolute zero during the negative wave.

2) The wave form of the negative wave at the mid-point of the pipe does not occur as expected theoretically.

3) The coefficient of rebound decreases with an increase in velocity.

4) Le Conte's method of analysis gives a very close approximation of the actual conditions.

T.W. Godfrey

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CHAPTER 1

INTRODUCTION

1 The Problem

It shall be the purpose of this thesis to investigate experimentally the pressure variations, in a closed conduit, caused by the sudden closure of a valve. The specific condition investigated shall be the case when there is a break in the water column due to a pressure drop to absolute zero during the negative portion of the pressure wave.

2 Definition of Water Hammer

The term water hammer specifically refers to the blow occuring in a pipe line when the velocity is suddenly checked. In the broader implications it involves any such pressure changes.[1]

3 Early Investigations

Although the existence of water hammer was known earlier, it was not until 1898 that a Russian, Joukovsky, set down the underlying principles in mathematical form. Joukovsky was the father of

1 D.S. Ellis, Elements of Hydraulic Engineering, (New York: D. Van Nostrand Co. Inc. 1947) P. 230

water hammer analysis as he not only set down the correct principles involved but verified them experimentally. There seems to be some conflict on the exact extent of Joukovsky's research. As far as the author can ascertain Joukovsky's work definitely covered instantaneous closure of the gate. There seems to be some conflict as to whether his work encompassed the influence of dead ends, the speed of gate closure and the effects of air chambers, air pockets and safety valves.

In 1902 an Italian, L. Allievi, published a treatise on the subject of slow closing valves. Unfortunately the treatise did not appear in English until 1925. In 1919 N.R. Gibson, an American published a solution to the problem of slow closing valves in a pipe line. It was this publication which revealed the existence of Allievi's work and lead to its publication in English.

Various men and organizations have since done extensive work on the problems of water hammer, but the three men mentioned above were the three men who laid most of the foundation.

CHAPTER 11

THEORY OF WATER HAMMER

1 General Theory of Instantaneous Closure

In the following analysis the action of friction is neglected. V is defined as the velocity, of the water, a as the velocity of the pressure wave, h_o as the static head on the valve and H_R as the change in head due to the sudden checking of the velocity, V. All dimensions are in feet and seconds.

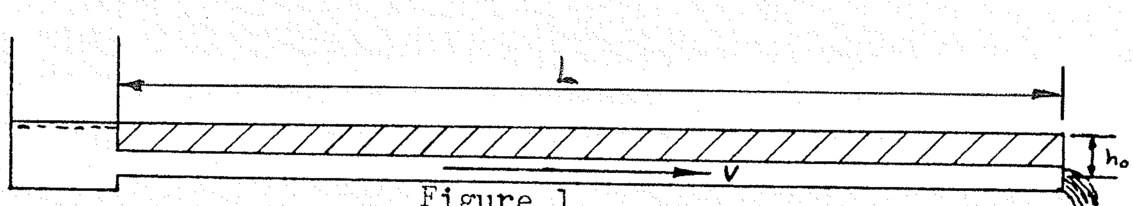


Figure 1

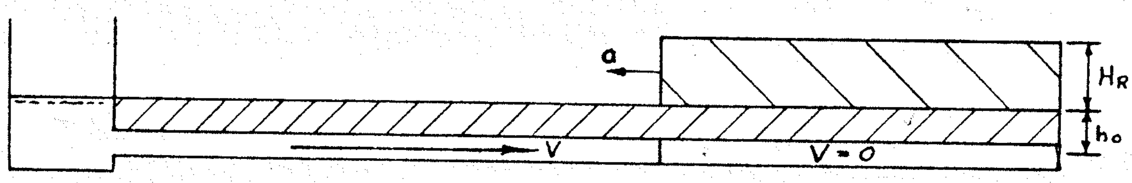


Figure 2

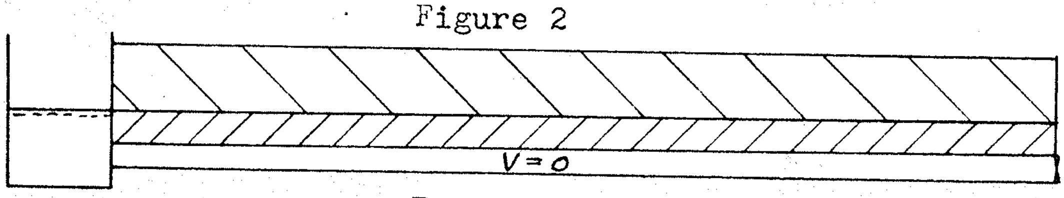


Figure 3

In figure 1 the water is flowing freely with a velocity V. The pressure throughout the pipe is h_o. The gate is closed instantaneously in figure 2 and the layer of water at the gate is stopped and compressed by the moving water behind it. The pressure of this layer of water rises by H_R to a new pressure of $h_o + H_R$. As each suceeding layer of water is stopped and compressed, the pressure wave of magnitude H_R moves toward the reservoir with a velocity a. In figure 3 the pressure wave has reached the reservoir and all the water is at rest and under a pressure of $h_o + H_R$. The time elapsed from closure of the gate is L/a.seconds.

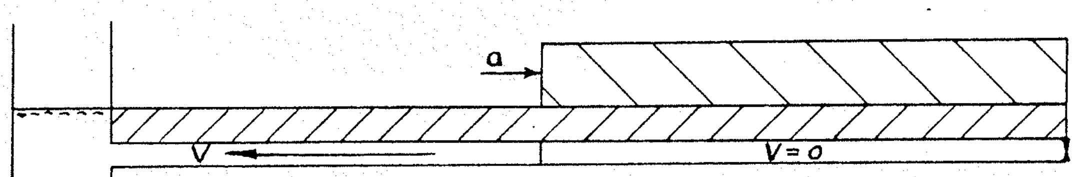


Figure 4

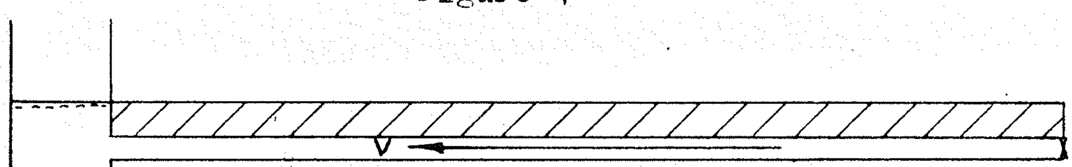


Figure 5

The system is now greatly unbalanced as there is nothing to confine the high pressure water in the pipe. The layer of water adjacent to the reservoir consequently flows into the reservoir. Similarily, layer by layer the pressure is relieved as the water begins to flow toward the reservoir. The high pressure wave retreats to the gate with a velocity a as shown in figure 4. In figure 5 the pressure is back to normal throughout the entire pipe and the entire column of water has a velocity V toward the reservoir. The time elapsed from closure of the gate is now 2L/a seconds.

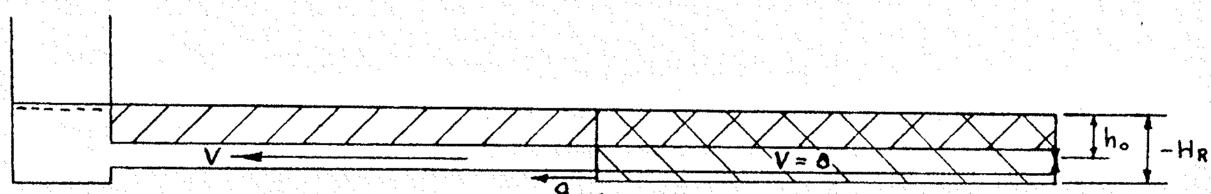


Figure 6

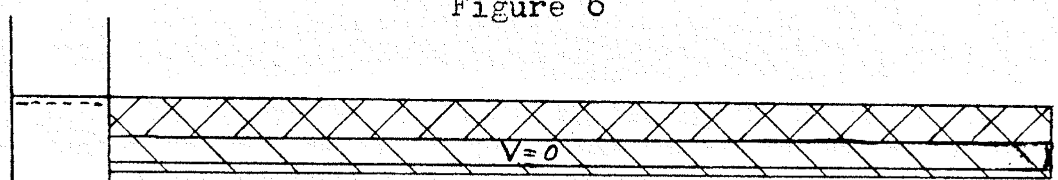


Figure 7

In figure 6 the layer of water adjacent to the gate attempts to flow away from the gate and is immediately stopped. The pressure of this layer of water drops to a value of $h_o - H_R$. Each successive layer of water is stopped and undergoes a pressure reduction. This negative pressure wave travels toward the reservoir as shown in figure 6, with a velocity a. In figure 7 the pressure wave has reached the reservoir and the entire column of water is at rest and under a pressure of $h_o - H_R$. The time elapsed from closure of the gate is 3L/a seconds.

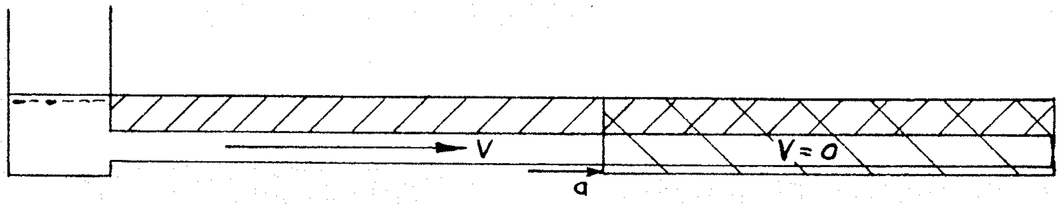


Figure 8

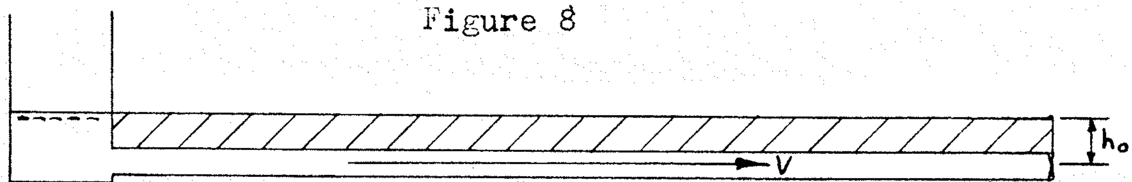
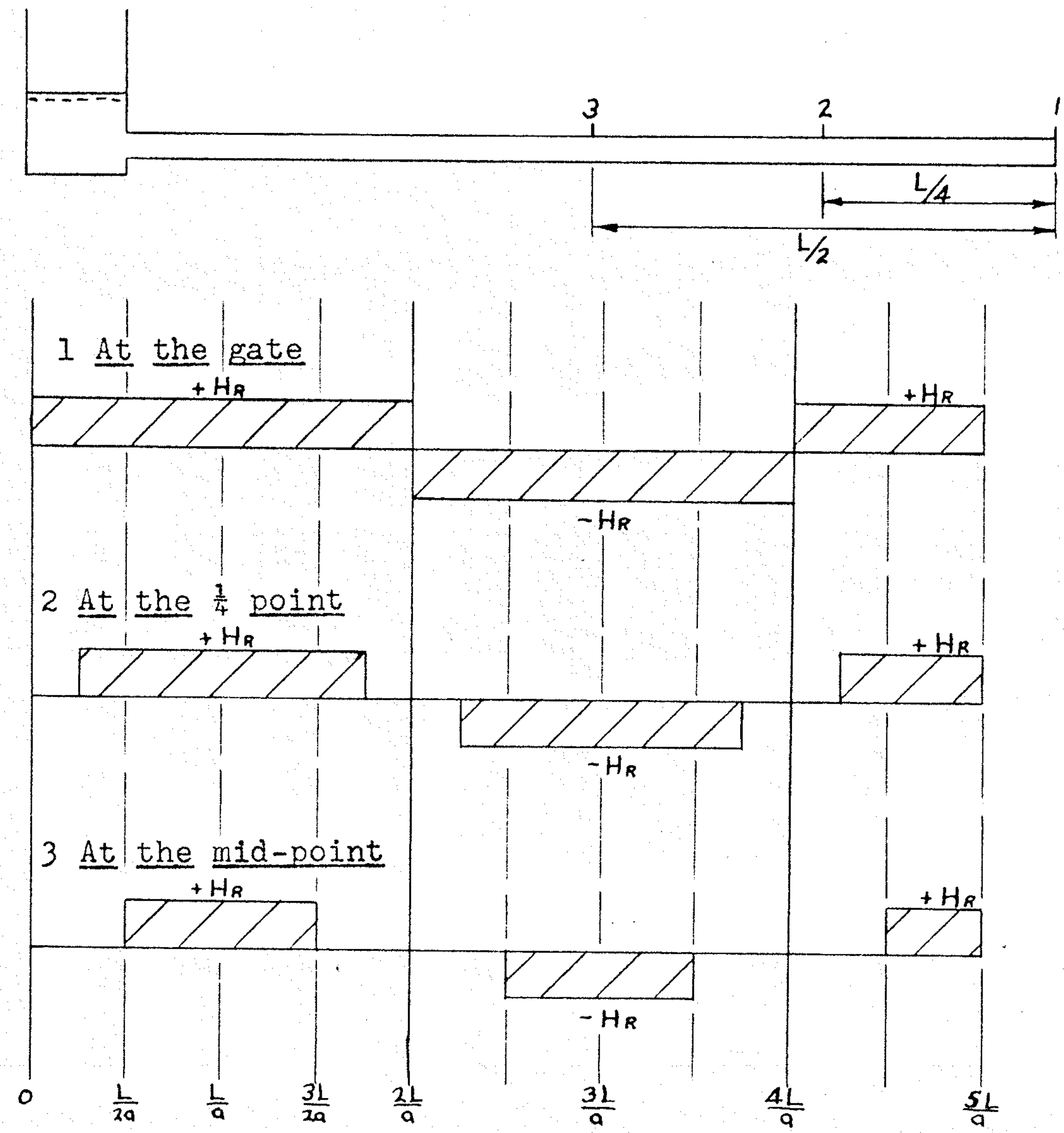


Figure 9

Oncemore the system is unbalanced and the water begins to flow toward the gate. Layer by layer the pressure returns to normal as the low pressure wave retreats to the gate with a velocity a. In figure 9 the pressure is back to normal (h_o) and the water is oncemore flowing toward the gate with a velocity V. The time elapsed from closure of the gate is 4L/a seconds.

The pressures analysed above would repeat for an infinite period of time if there was no friction present. The magnitudes of the pressure waves are reduced by friction until the water hammer dies out.

2 Pressure Variation Along the Pipe



3 Conditions for Instantaneous Closure

For the following analysis it will be assumed that the gate closure occurs in a number of equal steps. The first increment of closure causes a pressure rise which travels toward the reservoir with a velocity a. Each succeeding increment of closure causes a corresponding pressure rise as shown in figure 10.

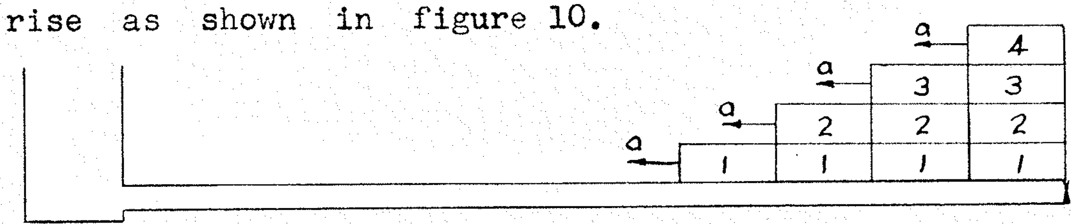


Figure 10

A choice of very small increments of gate closure would result in a pressure front as shown in figure 11.

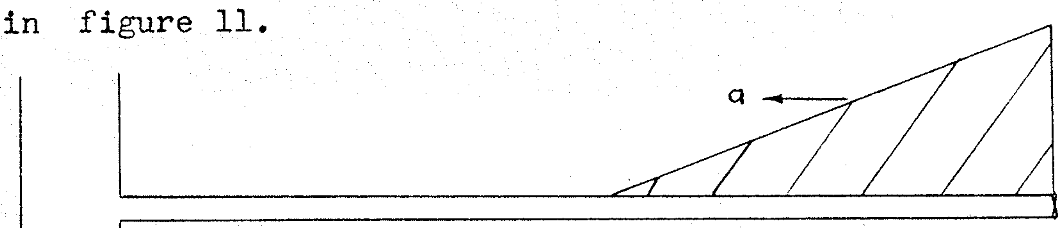
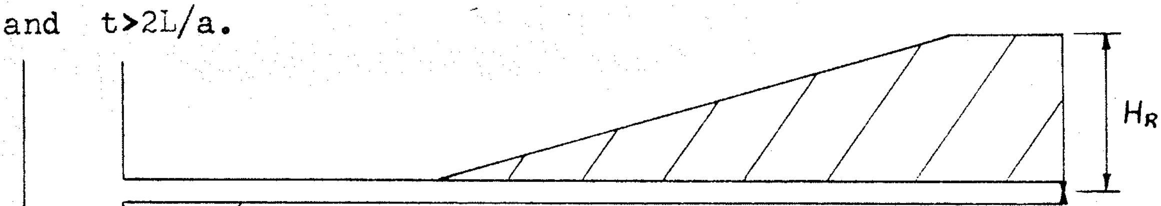


Figure 11

Now, let us consider various closure times for the gate, namely $t<L/a$, $t=L/a$, $L/a<t<2L/a$, $t=2L/a$ and $t>2L/a$.



$t<L/a$

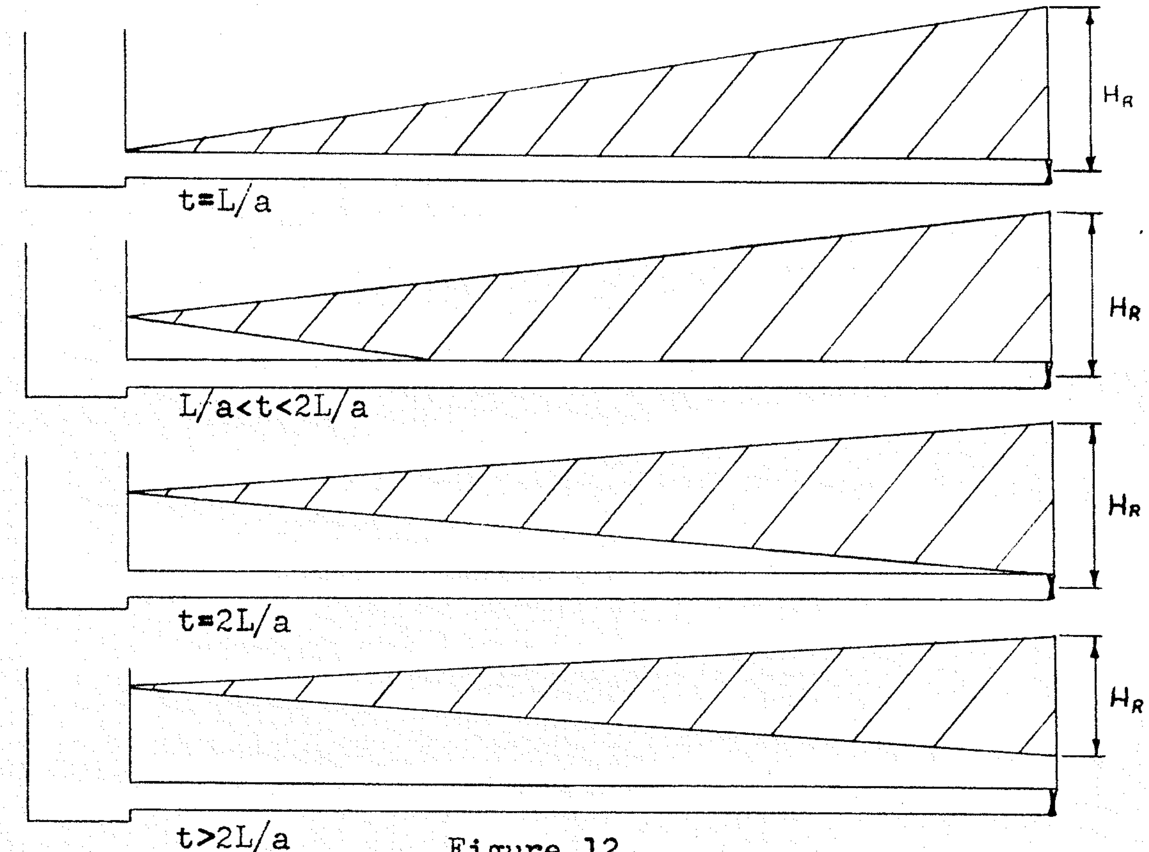
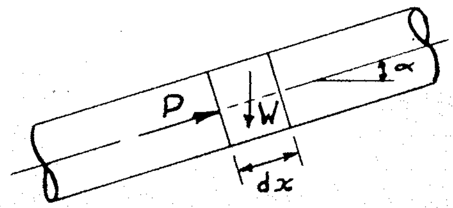


Figure 12

It will be noted that for closure times less than or equal to $2L/a$ a maximum pressure (H_R) is developed at the gate. The pressure is somewhat smaller as soon as the closure time exceeds $2L/a$. The term instantaneous closure is applied in all cases in which the maximum pressure occurs at the gate, i.e. when $t \leq 2L/a$ seconds. If the closure takes place in a length of time greater than $2L/a$ the gate would be classified as "slow closing" and will not be dealt with in this thesis.

4 Allievi's Equations

The fundamental equation for variable flow in a closed conduit, neglecting friction is;



$$\frac{\partial p}{\partial x} = R + \frac{W}{g}\frac{d^2x}{dt^2}$$

In the case shown in figure 12 $R = W\sin\alpha$
$= wAdx\ \sin\alpha$

Consider the case of a horizontal pipe then $R = 0$

$$\frac{\partial p}{\partial x} = \frac{W}{g}\frac{d^2x}{dt^2}$$

The velocity of the liquid $= V = \frac{dx}{dt} = \frac{\partial x}{\partial t}$ since x is along the axis of the conduit

$$\frac{\partial^2 x}{\partial t^2} = \frac{\partial}{\partial t}\left(\frac{\partial x}{\partial t}\right) = \frac{\partial V}{\partial t}$$

V varies with x , writing the complete derivative

of V: $\frac{dV}{dt} = \frac{\partial V}{\partial t} + \frac{\partial V}{\partial x}\frac{dx}{dt}$

$$= \frac{\partial V}{\partial t} + V\frac{\partial V}{\partial x}$$

$$= \frac{\partial^2 x}{\partial t^2} + V\frac{\partial V}{\partial x}$$

$$\frac{\partial^2 x}{\partial t^2} = \frac{dV}{dt} - V\frac{\partial V}{\partial x}$$

but $\frac{\partial p}{\partial x} = \frac{W}{g}\frac{\partial^2 x}{\partial t^2}$

$$\frac{\partial p}{\partial x} = \frac{W}{g}\left(\frac{dV}{dt} - V\frac{\partial V}{\partial x}\right) \qquad \ldots\ldots\ldots\ldots\ldots\ 1$$

Since $\frac{\delta V}{\delta x}$ is very small relative to $\frac{dV}{dt}$ due to the instantaneous character of water hammer we may write

$$\frac{\delta p}{\delta x} = \frac{W}{g}\frac{dV}{dt}$$

also $\frac{dV}{dt} = \frac{\delta V}{\delta t} + \frac{\delta V}{\delta x}\frac{dx}{dt}$

becomes $\frac{dV}{dt} = \frac{\delta V}{\delta t}$

$$\frac{\delta p}{\delta x} = \frac{W}{g}\frac{\delta V}{\delta t} \qquad \dots\dots\dots\dots\dots\dots \quad 2$$

Now $p = w\,\delta h$

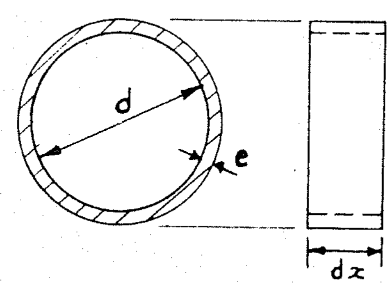
$$\frac{w\,\delta h}{\delta x} = \frac{w}{g}\frac{\delta V}{\delta t}$$

$$\delta h = \frac{\delta V}{g}\frac{\delta x}{\delta t}$$

$\frac{\delta x}{\delta t}$ = the velocity of the pressure wave = a

$$\Delta h = \frac{\Delta V}{g}\,a \qquad \dots\dots\dots\dots\dots\dots \quad 3$$

Consider an element, dx, of a pipe
Find the volume of water stored in length dx during a time, dt, due to



1 the elasticity of the pipe

2 the compressibility of the water

Due to the elasticity of the pipe

The symbol δp will be used for the term $\frac{\delta p}{\delta t}\,dt$

$$E = \frac{\text{stress}}{\text{strain}}$$

Stress in the pipe wall $= \frac{Pd}{2e}$

Due to an increment of pressure δp the stress is $\frac{\delta pd}{2e}$

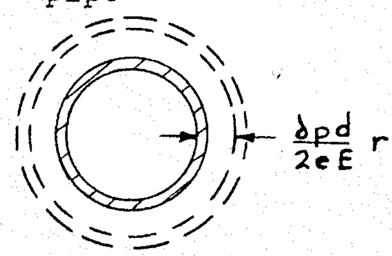
thus unit strain $= \frac{\delta pd}{2eE}$ (circumferential)

This value of unit strain is also equal to the unit change in the radius r.

Therefore the change in area of the pipe

is $= \left(\frac{\delta pd}{2eE}\, r\right) \pi d$

$= \frac{\delta p \pi d^3}{4eE}$



The change in volume $= \frac{\delta p \pi d^3}{4eE}\, dx$

$$= \frac{\pi d^3}{4eE} \frac{\delta p}{\delta t}\, dt\, dx \quad \ldots\ldots \text{ a}$$

Due to the compressibility of the water

By definition $k = \frac{\delta p}{\text{unit change in volume}}$

Change in volume = Volume × unit change in volume

$$= \frac{\pi d^2}{4}\, dx \;\; \frac{1}{k} \frac{\delta p}{\delta t}\, dt$$

$$= \frac{\pi d^2}{4k} \frac{\delta p}{\delta t}\, dt\, dx \quad \ldots\ldots\ldots\ldots \text{ b}$$

The total volume change $= a + b$

$$= \frac{\pi d^3}{4eE} \frac{\delta p}{\delta t}\, dt\, dx + \frac{\pi d^2}{4k} \frac{\delta p}{\delta t}\, dt\, dx$$

The total volume change must be equal to the difference in the quantity of water flowing into and out of the length dx in the time dt.

The total volume change $= \partial Q dt = (Adx)\dfrac{\partial V}{\partial x}\, dt$

Equating the total volume changes and simplifying

$$\frac{\partial V}{\partial x} = \frac{\partial p}{\partial t}\left(\frac{d}{Ee} + \frac{1}{k}\right)$$

$$\frac{\partial x}{\partial t} = a = \frac{\partial V}{\partial p}\left(\frac{1}{\frac{d}{eE} + \frac{1}{k}}\right)$$

also $\dfrac{\partial p}{\partial x} = \dfrac{w}{g}\dfrac{\partial V}{\partial t}$ therefore $\dfrac{\partial V}{\partial p} = \dfrac{\partial t}{\partial x}\dfrac{g}{w} = \dfrac{g}{aw}$

$$a = \frac{g}{aw}\left(\frac{1}{\frac{d}{Ee} + \frac{1}{k}}\right)$$

$$a = \sqrt{\frac{1}{\frac{w}{g}\left(\frac{d}{Ee} + \frac{1}{k}\right)}}$$

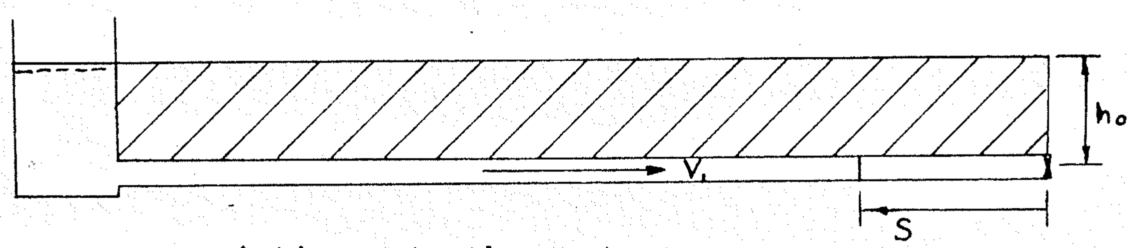
It is usually desirable to use the following units:

- a - feet/sec.
- w - pounds/cubic foot
- g - feet/sec./sec.
- d - inches
- e - inches
- E - pounds/square inch
- k - pounds/square inch

in which case the equation becomes $a = \dfrac{12}{\sqrt{\frac{w}{g}\left(\frac{d}{Ee} + \frac{1}{k}\right)}}$ 4

5 Ideal Concept of the Problem

The special type of water hammer under consideration is one in which the full negative pressure wave can not develop as it is limited by absolute zero pressure (vacuum).



Pressure variation at the gate:

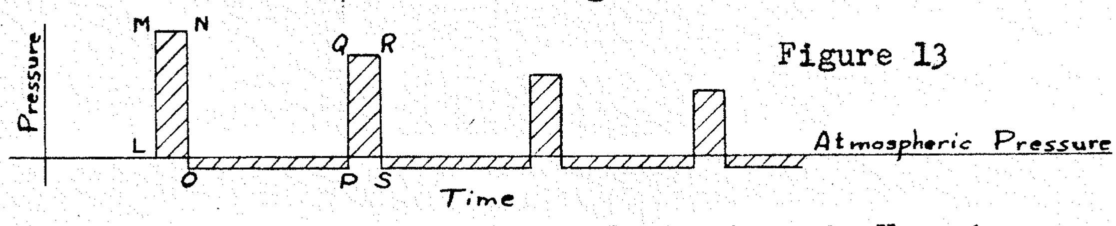


Figure 13

Let h_o be the initial head and V_1 the initial velocity. The valve is instantaneously closed at a time corresponding to LM and a positive pressure wave is formed as previously discussed. The time MN is equal to 2L/a seconds. At a time corrsponding to NO the water begins to flow away from the valve with a velocity V and the pressure drops to absolute zero. The water continues to flow away from the valve until such time as it uses up all of its kinetic energy in overcoming friction, the head h_o, and atmospheric pressure h_a. The water column is now at rest and begins to flow toward the valve once more under the head $h_o + h_a$. The water strikes the valve with a velocity V at a time corresponding to PQ and a second positive pressure wave occurs. The cycle repeats itself with the magnitudes of the positive waves decreasing in magnitude and the periods of the negative waves also decreasing in magnitude. The time QR = the time MN = 2L/a.

The pressure variation at the center of the pipe would be as shown in figure 14.

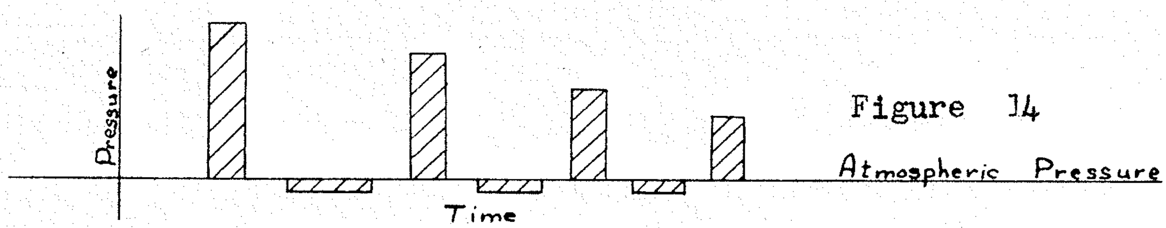


Figure 14

The following analysis was given by Le Conte in a paper on the subject "Experiment and Calculation on the Resurge Phase of Water Hammer".

From experimental results it is obvious that the velocity of approach at M in figure 13 is greater than the velocity of rebound at N. This may be expressed as $V_o = CV$ where V_o = the velocity of rebound and V = the velocity of approach. Le Conte states that he found the coefficient C was nearly constant for a given set of waves and was approximately constant for a given pipe line. The coefficient was found to decrease with increasing velocity.

Velocity is not only destroyed on rebound but also due to pipe friction and to losses as the column enters the reservoir.

Let f = the friction factor (assumed constant)
V_o = the initial velocity
V = any value of the velocity thereafter
L = the length of the pipe
d = the diameter of the pipe
A = the cross-sectional area of the pipe
h_o = the head in the pipe under normal conditions
h_a = atmospheric pressure
t_1 = the time for the column of water to come to rest.
t_2 = the time for the return of the column to the valve.
S = the distance the column of water travels away from the gate while the velocity changes from V to zero.

The force equation on rebound becomes:

$$A\gamma(h_o + h_a) + A\gamma f \frac{L}{d}\frac{V^2}{2g} = \frac{LA\gamma}{g}\frac{dV}{dt} \qquad \text{............. 1}$$

Integrating we find

$$t_1 = \frac{LV''}{g(h_o + h_a)} \tan^{-1}\frac{V_o}{V''} \qquad \text{..................... 2}$$

$$\text{where} \quad V'' = \sqrt{\frac{2g(h_o + h_a)}{f(L/d)}}$$

Assuming the column to hold together we may find S by integrating equation 1 in the form:

$$A\gamma(h_o + h_a) + A\gamma f \frac{L}{d}\frac{V^2}{2g} = \frac{LA\gamma}{g} V \frac{dV}{ds}$$

$$\text{Thus} \quad S = \frac{L(V'')^2}{g(h_o + h_a)} \, \tfrac{1}{2} \log_e \left[1 + \left(\frac{V_o}{V''}\right)^2\right] \qquad \text{.......... 3}$$

The force equation for the return of the water column becomes: $A\gamma(h_o+h_a) - A\gamma\left(1+f\frac{L}{d}\right)\frac{V^2}{2g} = \frac{LA\gamma}{g}\frac{dV}{dt}$ ... 4

Integrating $t = \frac{LV'}{g(h_o+h_a)} \tanh^{-1}\frac{V}{V'}$ 5

$$\text{where } V' = \sqrt{\frac{2g(h_o+h_a)}{1+f(L/d)}}$$

If equation 5 is written in the form:

$$V = \frac{ds}{dt} = V' \tanh \frac{g(h_o+h_a)}{LV'}t \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ 6$$

$$\text{or } ds = V' \tanh \frac{g(h_o+h_a)}{LV'}t\,dt \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ 7$$

Integrating

$$S = \frac{L(V')^2}{g(h_o+h_a)} \log_e \cosh \frac{g(h_o+ha)}{LV'}t \quad \ldots\ldots\ 8$$

Equating S from equations 3 and 8 and putting $t=t_2$

$$\log_e \cosh \frac{g(h_o+h_a)}{LV'}t_2 = \frac{1}{2}\left(\frac{V''}{V'}\right)^2 \log_e\left[1+\left(\frac{V_o}{V''}\right)^2\right]$$

$$= n \log_e\left[1+\left(\frac{V_o}{V''}\right)^2\right]$$

$$\text{or} \quad \cosh \frac{g(h_o+h_a)}{LV'}t_2 = \left[1+\left(\frac{V_o}{V''}\right)^2\right]^n \quad \ldots\ldots\ldots\ldots\ 9$$

$$\text{where } n = \frac{1}{2}\left(\frac{V''}{V'}\right)^2$$

It is now possible to calculate t_1 from equation 2 and t_2 from equation 9 thus obtaining the total duration of the negative wave. Following the first cycle of waves the new velocity of approach may be calculated from equation 6. This process is repeated for the entire set of waves.

F.N. Wood of Queens University presented a paper on the subject "Graphical Solutions of Partial Differential Equations with Engineering Applications" This graphical method applies to all physical problems that satisfy the two partial differentials $\frac{\delta s}{\delta t} = k_1 \frac{\delta V}{\delta x}$ and $\frac{\delta s}{\delta x} = k_2 \frac{\delta V}{\delta t}$ where s and V are two variables which depend on the two variables x and t.

For the particular problem under study in this thesis these two general equations are of the form $\frac{w}{g}\frac{\delta V}{\delta t} = -\frac{\delta p}{\delta x}$ and $\frac{\delta p}{\delta x} = -\left(\frac{1}{k} + \frac{1}{E}\frac{d}{e}\right)\frac{\delta p}{\delta t} = -\frac{1}{k_1}\frac{\delta p}{\delta t}$

where k = the bulk modulus of elasticity of water.
w = the weight of a unit volume of water.
E = the modulus of elasticity of the pipe wall.
d = the diameter of the pipe.
e = the thickness of the pipe
V,p = the velocity and pressure at any section (x,t)

Wood calculates the theoretical pressure waves for various ratios of R. It should be noted that this graphical analysis very often shows that the initial positive pressure is not always the maximum pressure. The ratio of 0.45 (not shown) has a maximum pressure of 3.5 times the initial positive pressure. The waves that are of particular interest in this thesis are shown in figure 15.

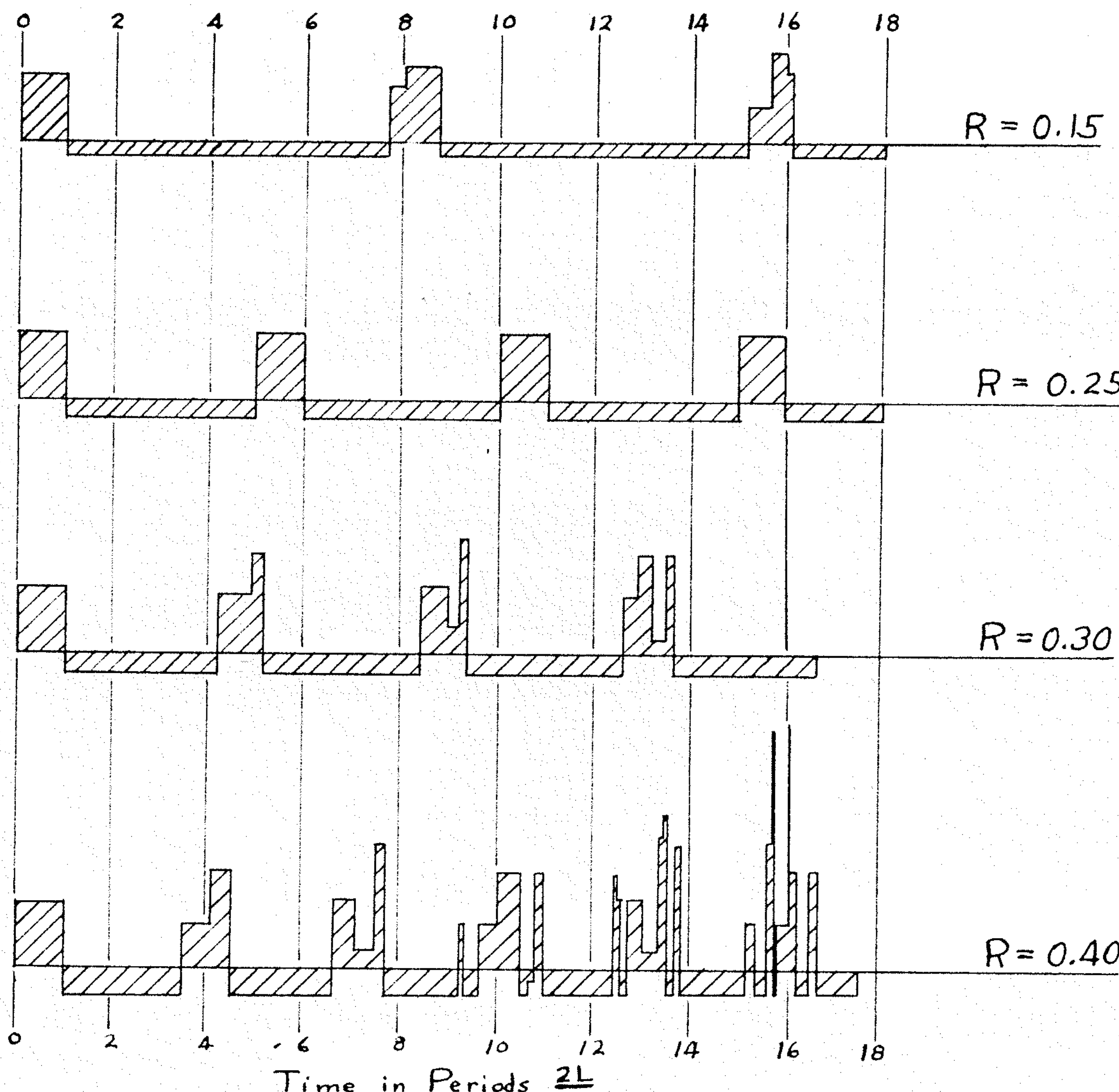


Figure 15

$R = \frac{h_o + h_a}{h_r}$ where h_o = the static head on the valve
h_a = atmospheric pressure
h_r = the pressure rise for instantaneous closure of the valve.

CHAPTER 111

LABORATORY PROCEDURE

1 <u>Apparatus</u>

a) The pipe and reservoir:

The tests for this thesis were carried out on a two inch standard steel pipe 54.7 feet long. The pipe was connected to a tall cylindrical tank capable of producing a static head of approximately 27.4' above the entrance to the pipe. The pipe was suspended from the ceiling by means of five steel rods and the sideways movement of the pipe was controlled by four steel rods extending to the wall. The maintenance of a constant head was facilitated by a six inch overflow pipe attached to the reservoir. Once the reservoir was full, water was fed to it by a two inch water main. This inflow to the reservoir was maintained at such a level as to ensure a continual overflow, regardless of the quantity of water being used for the tests.

b) The valve:

The type of valve used to produce the water hammer was a quick opening gate valve of the cam action variety. This type of valve was made of brass, with a solid wedge disc which could be closed by a one-quarter turn of the lever. The valve has been constructed to withstand the shock of a sudden closure. It should be noted here that the valve was designed for manual operation. Consequently, it has been designed to withstand forces of closure which one might expect to occur under these circumstances. The manufacturer states the working pressure of this valve as two hundred pounds of cold water (non-shock).

c) The pressure cell:

A brass pressure cell was used to measure the pressure fluctuations in the pipe. The cell dimensions were as shown in figure 20. The pressure cell was attached to the pipe by means of a small threaded nipple. Nipples were provided at the gate , the one-quarter point and at the mid-point of the pipe. These nipples were welded to the pipe and provided with plugs when not in use. The type of strain gauge circuit to be used for the pressure cell was the wheatstone bridge. A small plexi-glass plate was made to hold the four terminal posts (A,B,C,D) as shown in figure 21. The primary concern in its construction was to ensure that none of the terminals was grounded to the cell.

d) The oscilloscope:

The pressure variations of the water hammer

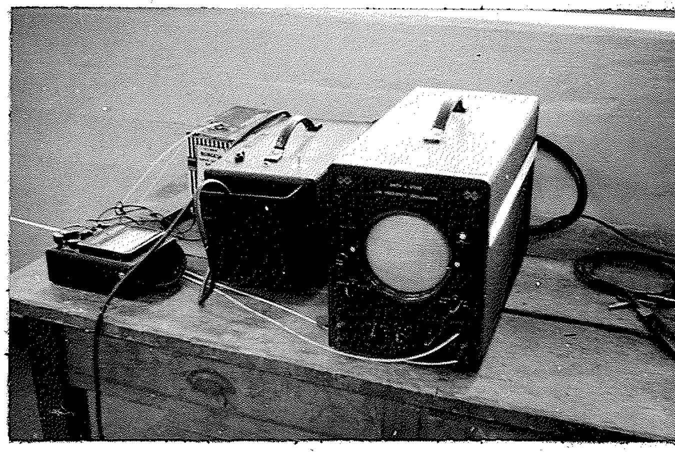


Figure 17

The Oscilloscope

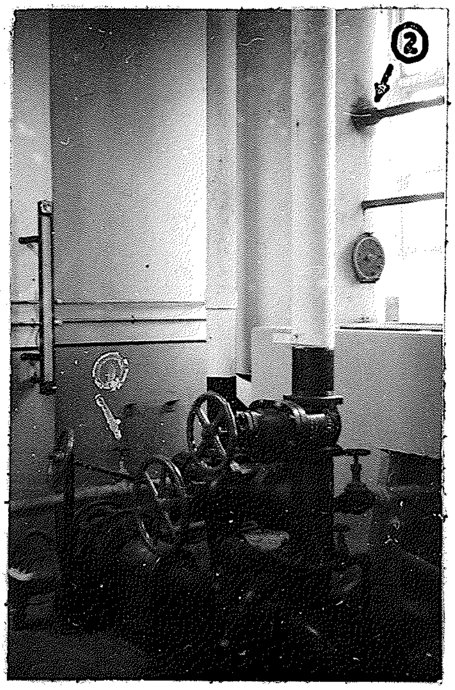


Figure 18

The Pump and Resevoir with gate valve at 1 and test pipe at 2.

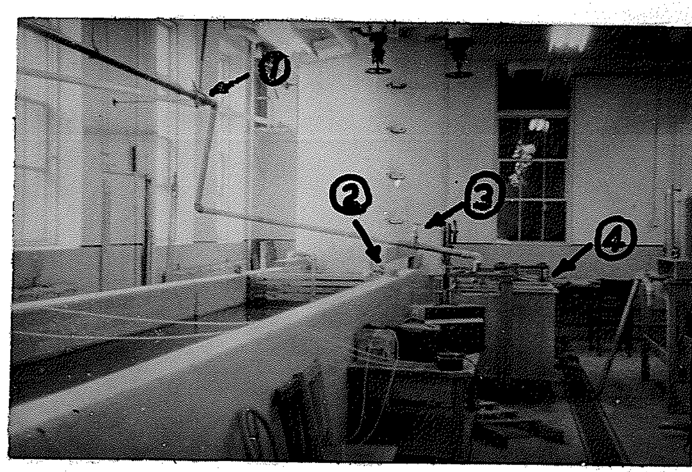


Figure 19

The General Layout with quick-opening valve at 1, overcenter lever at 2, gate valve at 3, and weighing tanks at 4.

PRESSURE CELL

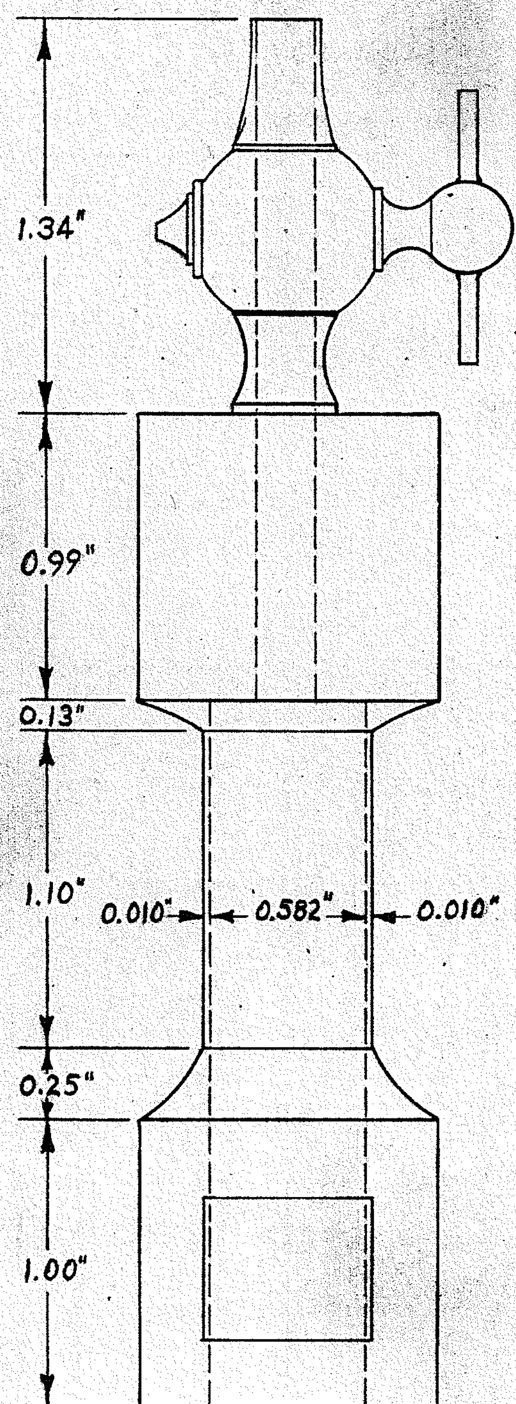


FIGURE 20

Gauge Locations

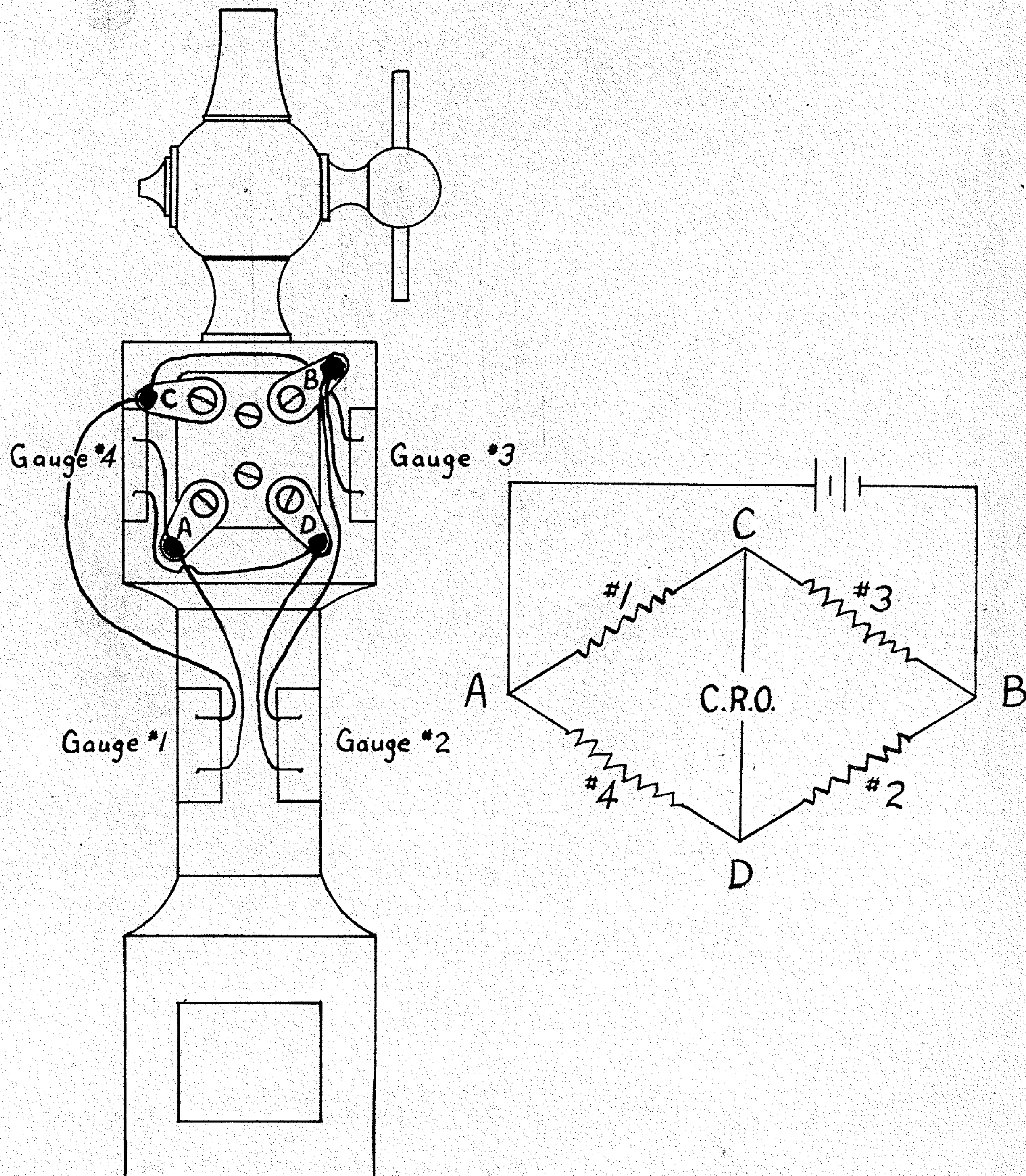


Figure 21

were recorded by a Smith and Stone low frequency oscilloscope, model L24S. The input voltage for the wheatstone bridge circuit was supplied by 22½ volt dry cell. The important feature of this oscilloscope was a built-in camera which enabled a trace of the pressure waves to be recorded on film. The camera automatically printed height lines at 1 millimeter spacing and timing lines at a spacing of 1/50 of a second.

e) Discharge:

A section of 2 inch (see figure 19) pipe was used to lead the discharge down to the measuring tanks. The velocity of the water in the pipe was controlled by a gate valve on this section of the pipe. This gate valve not only provided the means of velocity control, but also ensured that the test pipe was always full of water. The quick opening valve was always opened fully thus ensuring uniform times of closure. If the gate valve was not used the velocity would have had to be controlled by means of the quick opening valve. It was an advantage to have the valve (quick closing) surrounded by solid water columns on each face. This arrangement meant that there was no air in the pipe and also no air at the outside face of the valve during most of the duration of the water hammer.

f) The closing mechanism:

It was found to be necessary to close the quick opening valve in a time of approximately 1/40 of a second in order to obtain instantaneous closure. This meant that some mechanical means of closing the valve had to be found. It was finally decided to close the valve by means of a 24 inch constant tension spring (150#). The spring was attached at one end to an overhead pipe and at the other end to the lever of the valve. The spring was attached to the lever at about the one-third point so as to limit the amount of travel of the end of the spring.

The valve was opened and closed by means of a rope attached to an over-center lever as shown in figures 24 and 25. The over-center lever had to be made of thin steel tubing to limit its momentum on closure. A rubber pad had to be placed under the end of the lever to cushion its impact with the two by four on closure. The lever was provided with an extension which gave more leverage when opening the valve. This extension was removed before tripping the lever. The lever was

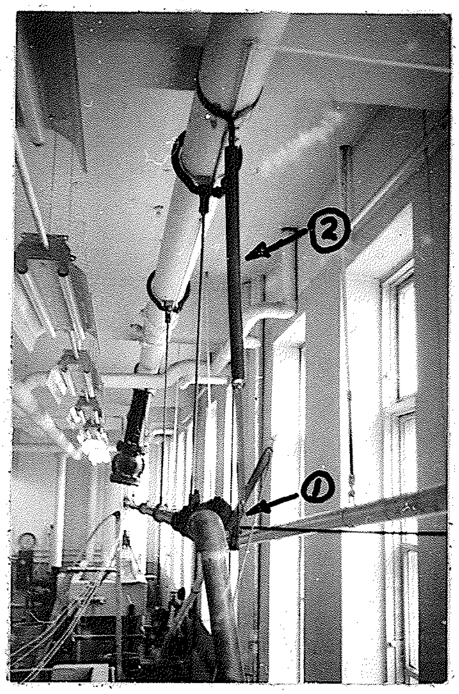


Figure 22

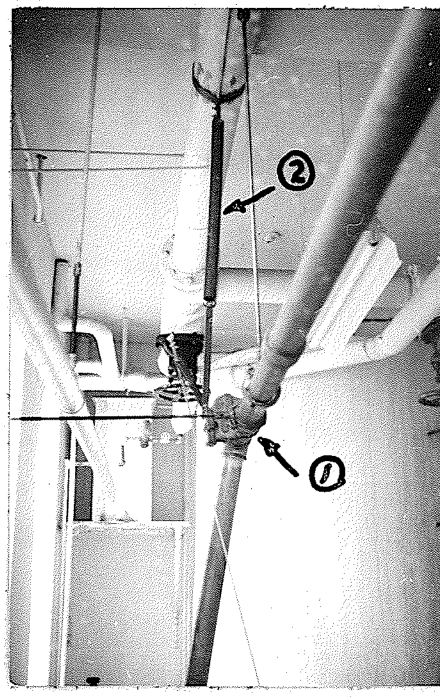


Figure 23

Quick-closing Valve
at 1, and spring at 2.

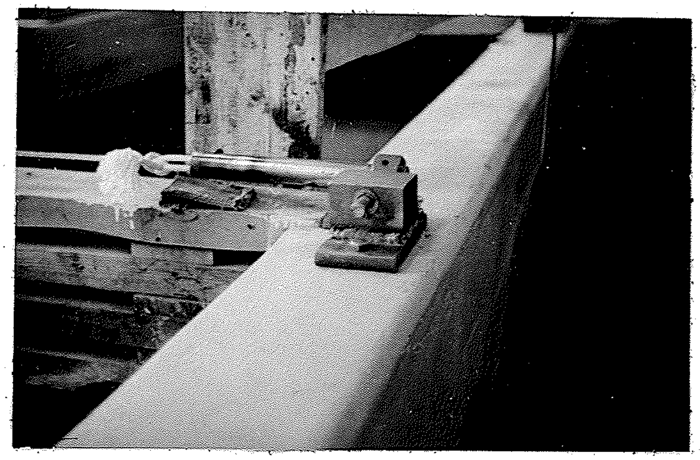


Figure 24

Overcenter Lever - closed

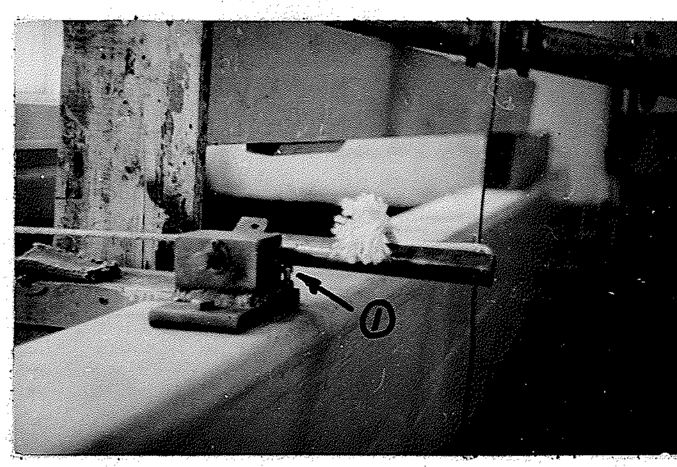


Figure 25

Overcenter Lever - open
with stop at 1.

constructed to have a rotation of 180 degrees from the closed to open positions. The minimum length of the lever was therefore limited by the length of travel of the valve handle. It was decided to allow about one-half inch for stretch in the rope. The lever was made 7.15 inches long to give a total travel of 14.30 inches.

g) The strain gauges:

SR-4 strain gauges , type C-10, were used in the wheatstone bridge circuit. These strain gauges have a resistance of 1000 ± 5 ohms and a gauge factor of $3.25 \pm 2\%$. The two active gauges were glued to the thin-walled section of the cell as shown in figure 21. The two dummy gauges were glued to the thick part near the top of the cell. The two active gauges were placed circumferentially around the cell for maximum sensitivity. The gauges were covered with a special wax to prevent any moisture from reaching the gauges. The effect of moisture is twofold i) it causes a breakdown of the insulation between the gauges and the pressure cell ii) it causes electro-chemical corrosion of the gauge wire due to electrolysis which causes a rise in resistance. Both of the above factors will result in a zero drift over any long period of time.[1] The lead wires for the strain gauges were soldered to their respective terminal posts as shown in figure 21.

2 Test Procedure

a) Calibration of the pressure cell:

In order to calibrate the pressure cell a known pressure was applied to the cell by means of an American Dead Weight Gauge Tester (see figure 27). The piston gives a pressure of 5 pounds per square inch and increments of twenty pounds per square inch were used in the calibration.

The circuit used for calibration of the pressure cell was as shown in figure 26. It will be noted that the only addition to the test circuit (figure 21) was a variable resistance (capacity 2 meg-ohms) shunted across one gauge. The reason for this resistance was to make it possible to obtain as nearly an initially balanced circuit as possible.

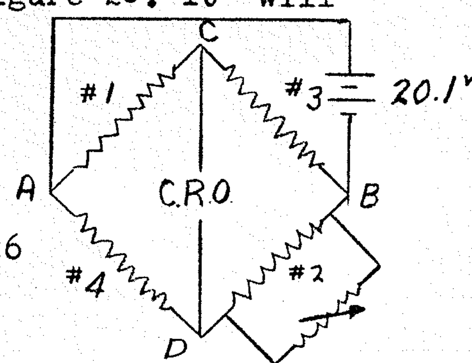


Fig. 26

1 W.B. Dobie, Electric Resistance Strain Gauges (London: The English Universities Press Limited, 1948) P. 11.

AMERICAN DEAD WEIGHT GAUGE TESTER

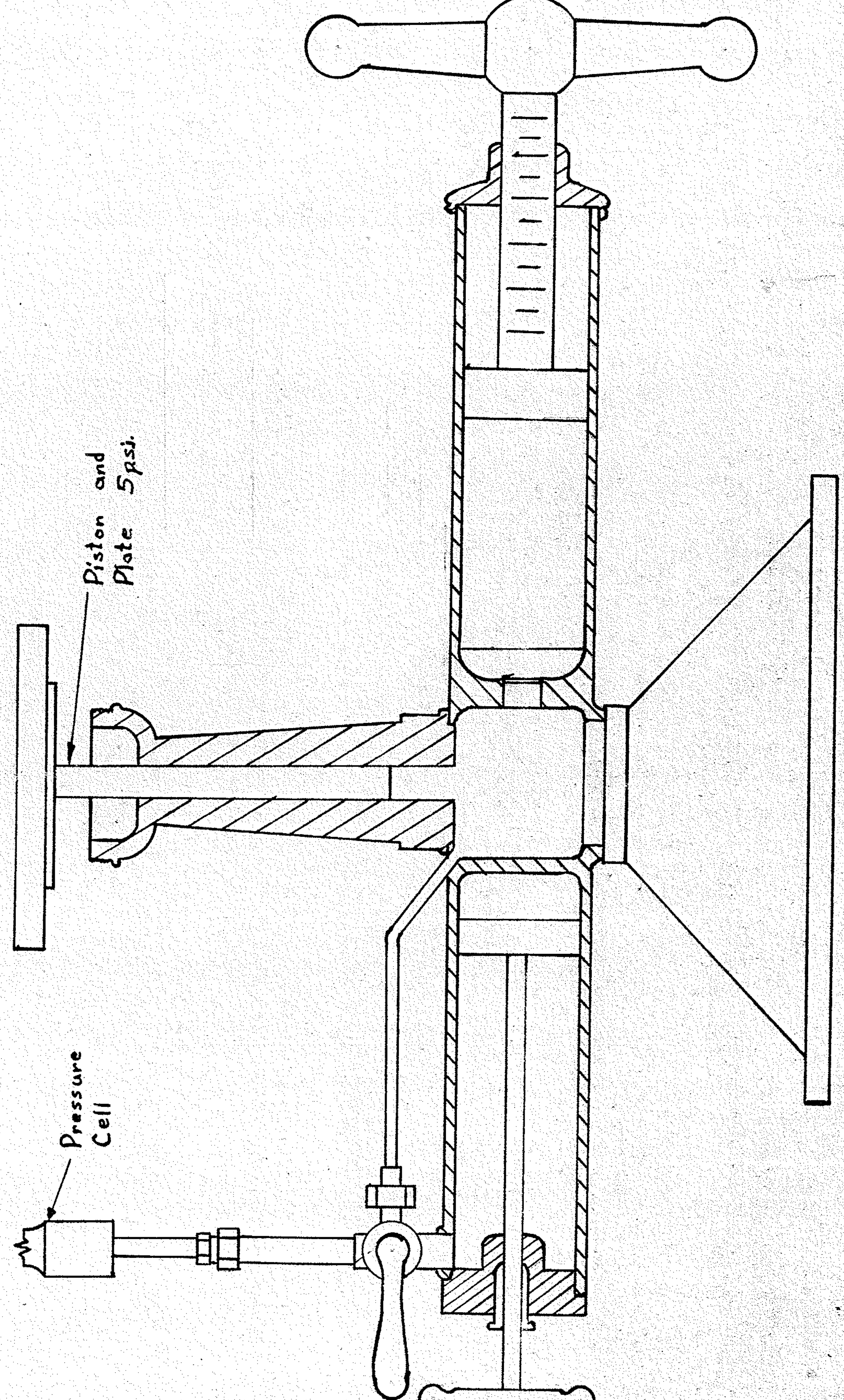


FIGURE 27

Any unbalance in the circuit was measured by shorting the circuit across the two input terminals of the oscilloscope. This shorting caused a deflection of the spot. To initially balance the circuit the variable resistance was adjusted until the deflection of the spot was a minimum. It was not possible to completely balance the circuit as the adjustment on the resistance was not delicate enough. Once the initial balance was set, the number of grid divisions of the deflection was recorded. This original balance was made at a pressure of 5 pounds per square inch.

The pressure was increased to 25 pounds per square inch and the deflection of the spot was measured and recorded. This procedure was repeated for pressures of 45, 65, and 85 pounds per square inch. The pressure was reduced to 5 pounds per square inch and the original deflection was checked. It was found that the zero was drifting and so several runs were made in as short a time as possible. The difference between successive deflections gives a value of grid divisions for increments of pressure of 20 pounds per square inch.

The attenuator was now switched to infinity and the deflection of the spot was recorded for a 1 milli-volt signal. This enabled a correlation, between the pressures and the milli-volt input to the oscilloscope, to be calculated.

The voltage of the dry cell was measured as this represented the input to the wheatstone bridge. The theoretical milli-volt output of the wheatstone bridge (input to the oscilloscope) was calculated for a given internal pressure of the cell. The actual milli-volt output of the circuit was also calculated from the calibration. From these two values the sensitivity of the pressure cell was calculated.

b) The tests:

The pressure cell was installed on the pipe to measure pressures at the gate. The lead wires were soldered to the terminals on the pressure cell and the leads for the battery were distinctly marked. A few trial runs were made to test the apparatus. The valve was manually operated during these trial runs. It was decided that a mechanical means of closing the valve would have to be designed. The spring type of mechanism was finally decided upon, and set up.

Preliminary calculations were carried out to determine the velocity of the pressure wave(a), the period of the pipe (2L/a) and the theoretical discharges which corresponded to various maximum pressure rises.

The first tests run were to consist of very low pressure rises. It was hoped to set the velocity at such a value that would allow the full negative pressure wave to develop. However, it was found that the pressure cell was also picking up a high frequency wave caused by the vibration of the pipe. This high frequency wave was, of course, superimposed on the water hammer wave which was a low frequency wave. Due to the difficulty involved in getting rid of this high frequency wave it was decided to abandon all low pressure tests and concentrate only on high pressure tests.

Three series of tests were run, at pressures of 200, 150 and 100 pounds per square inch. The procedure followed for these and all other tests was: 1) The velocity was adjusted by means of the gate valve until the pressure of the first positive wave as viewed visually on the oscilloscope was approximately the desired value.

2) The discharge was measured for as long a period of time as possible. This value was compared with the theoretical discharge.

3) The gate valve was adjusted until the theoretical discharge, corresponding to the desired pressure, was obtained.

4) The stop-cock at the top of the pressure cell was opened and allowed to drain for a few seconds to remove all air from the cell.

5) The 1 milli-volt signal was checked and set if required to the number of divisions of deflection used during the calibration.

6) Three sets of pressure waves were recorded on film and then a 1 milli-volt signal calibration was also recorded on the film.

Various points which had to be watched were: 1) Care had to be taken to be sure all of the air was removed from the cell.

2) After the valve was tripped for the first time, there was a considerable quantity of air bubbles in the water. Care had to be taken to allow the water to run for a sufficient length of time to drain all of this water from the

pipe before the valve was tripped a second time.

3) The face of the cathode ray tube had to be covered during all test runs in which film was being used. If this precaution was not taken light entering from the front of the tube clouded the film.

4) The reservoir was checked periodically, while adjusting the discharge, to be sure that water was coming down the overflow pipe i.e. to ensure that the head was constant.

The reservoir was drained and the high frequency wave was recorded on film. This pressure wave would give the worst possible condition, as there was no water to cushion the impact of the valve as there would be in an actual test.

Three more series of tests were conducted in an attempt to obtain pressure waves for Wood's R values of 0.15, 0.25 and 0.30.

The durations of the negative waves were calculated using Le Conte's theory. These theoretical values of time were compared with the actual values of time which measured from the films. The theoretical maximum and all other values of pressure were calculated from the approach velocities for each phase. These theoretical values of pressure were also compared with the actual test values.

The pressure cell was shifted to the mid-point of the pipe and three series of tests were carried out. The waves recorded were for pressures of approximately 100, 200 and 300 pounds per square inch. The durations of the negative waves were compared with those obtained from the pressure waves recorded at the gate. The only pressures calculated were the actual test values. The theoretical pressures could not be calculated because only the initial approach velocity was known or could be found.

The high frequency wave was recorded on film once more to see just what effect it had when the pressure cell was at the mid-point of the pipe. The films showing the high frequency wave were of great value in the interpretation of the water hammer waves.

One test run was made at a pressure, corresponding to an R value of 0.45. This was the pressure at which Wood states the maximum pressure should be 3.5 times the initial pressure rise.

All test results, comparisons and graphs are recorded in the following chapter.

CHAPTER 1V

DATA AND CALCULATIONS

1 Test Results

Table 1 - Calibration of the Pressure Cell

Pressure in cell - p.s.i.	Deflection of spot - grid divisions	Deflection increment for each 20 p.s.i. pressure increment
5	7.0	
		4.0
25	3.0	
		3.2
45	-0.2	
		3.7
65	-3.9	
		3.8
85	-7.7	
5	8.0	
		4.0
25	4.0	
		3.8
45	0.2	
		3.4
65	-3.2	
		3.6
85	-6.8	

SR-4 strain gauges , type C-10
-resistance 1000 ± 5 ohms
-gauge factor $3.25 \pm 2\%$

1 milli-volt signal 4 divisions

Input voltage 20.1 volts

Average deflection increment for each 20 p.s.i pressure increment 3.7 divisions.

Table 2 - Test Data

Film no.	Velocity in f.p.s.	Pressure from discharge in p.s.i.	Pressure from curve in p.s.i.	R $=h_o/h_a$ / H_R	Rebound Coeff. - C First rebound	Rebound Coeff. - C All other rebounds
1	3.68	221.0	218.0	0.120	0.91	0.70
1 LW	3.68	221.0	218.0	0.120	0.94	0.86
2	1.49	89.7	87.2	0.298	0.97	0.79
3	1.80	108.0	108.5	0.247	0.90	0.74
4	3.42	205.0	197.6	0.130	0.91	0.71
6	1.86	111.5	111.0	0.238	----	----
7	3.56	214.0	215.0	0.128	----	----
8	4.88	293.0	284.0	0.091	----	----

Films no. 1, 1LW, 2, 3, and 4 were recorded for pressures at the gate.

Films no. 6, 7, and 8 were recorded for pressures at the mid-point of the pipe.

The test pipe was a standard 2 inch pipe of:
- -diameter - 2.067 inches
- -thickness - 0.154 inches
- -area - 0.0234 square feet
- -length - 54.7 feet

The velocity of the pressure wave was 4460 f.p.s.
The period of the pipe was 0.0246 seconds.

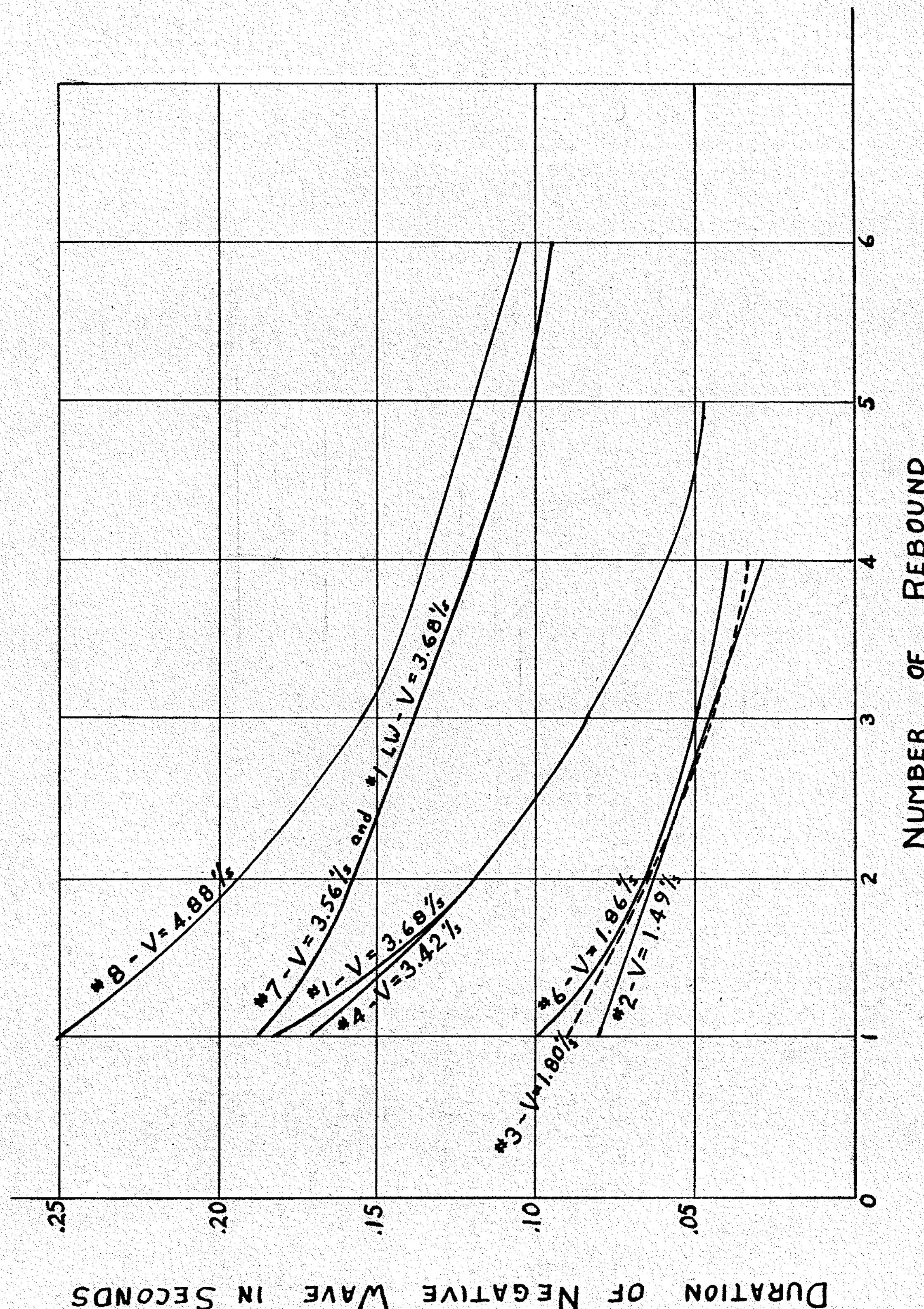
Table 3 - Summary of the pressures of the positive waves

Film no.	1		1 LW	
	Calculated	From curve	Calculated	From curve
Pressure psi. for peak no.1	221.0	218.0	221.0	218.0
2	196.0	196.0	205.0	207.0
3	136.0	141.0	174.0	174.0
4	95.0	109.0	148.0	152.0
5	65.5	82.0	126.0	120.0
Film no.	2		3	
	Calculated	From curve	Calculated	From curve
Pressure psi. for peak no.1	89.7	87.2	108.0	108.5
2	85.5	65.5	96.0	98.0
3	63.0	49.2	69.0	76.0
4	49.5	33.0	50.0	54.5
Film no.	4		6	
	Calculated	From curve	Calculated	From curve
Pressure psi. for peak no.1	205.0	197.0	111.5	111.0
2	184.0	179.0	-----	89.5
3	130.0	129.0	-----	78.0
4	91.0	99.0	-----	54.6
Film no.	7		8	
	Calculated	From curve	Calculated	From curve
Pressure psi. for peak no.1	214.0	215.0	293.0	284.0
2	-----	172.0	-----	224.0
3	-----	149.0	-----	190.0
4	-----	130.0	-----	153.0
5	-----	114.0	-----	136.0
6	-----	103.0	-----	109.0

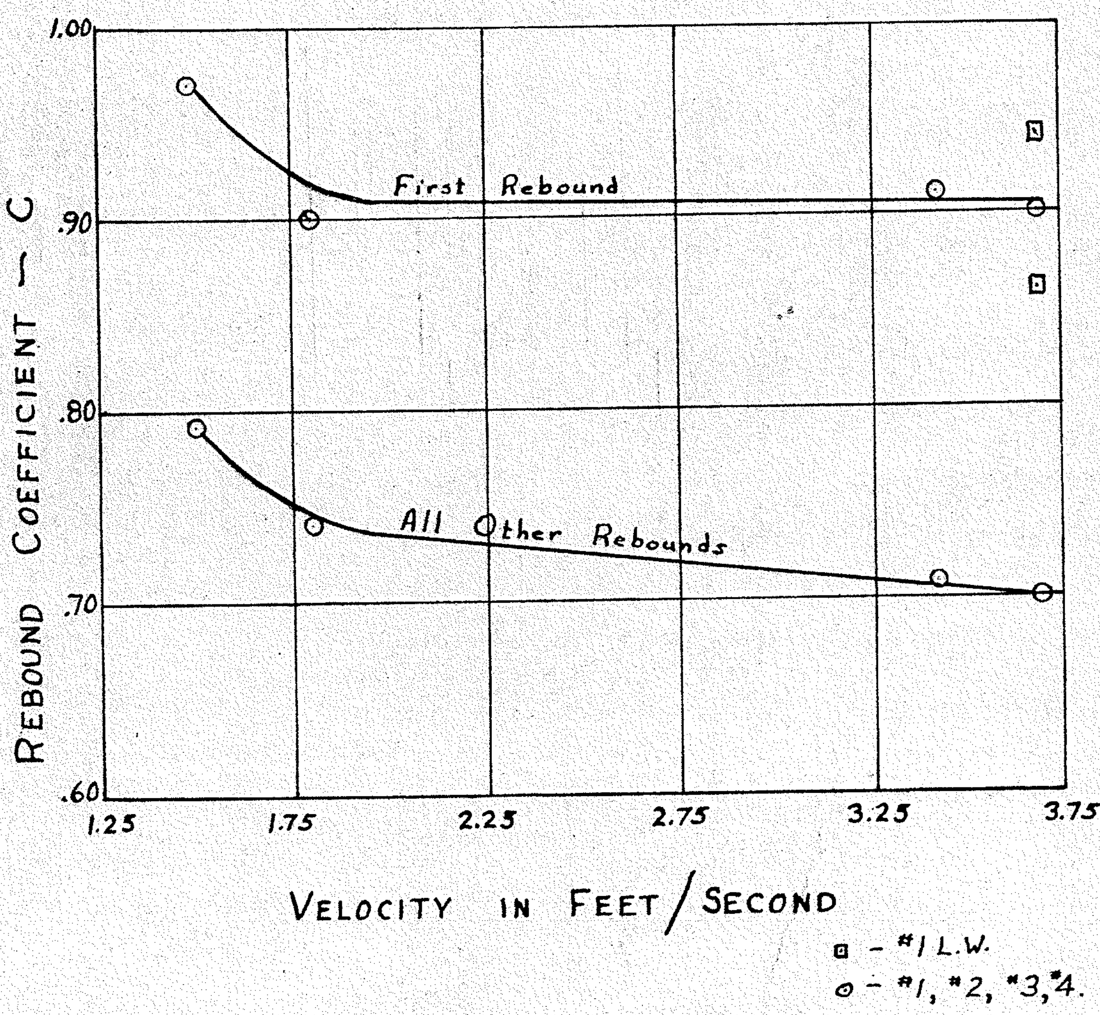
Table 4 - Summary of the Durations of the Negative Waves

Film no.	1		1 LW	
	Calculated	From curve	Calculated	From curve
Time for phase 1	0.1826	0.1850	0.1905	0.1900
2	0.1247	0.1200	0.1614	0.1600
3	0.0872	0.0850	0.1373	0.1390
4	0.0607	0.0600	0.1166	0.1200
5	0.0422	0.0480	0.0992	0.1000
Film no.	2		3	
Time for phase 1	0.0793	0.0800	0.0896	0.0900
2	0.0619	0.0621	0.0649	0.0651
3	0.0458	0.0481	0.0466	0.0471
4	0.0254	0.0280	0.0332	0.0340
Film no.	4		6	
Time for phase 1	0.1713	0.1720	------	0.1000
2	0.1200	0.1200	------	0.0667
3	0.0848	0.0851	------	0.0500
4	0.0588	0.0601	------	0.0400
Film no.	7		8	
Time for phase 1	------	0.1880	------	0.2510
2	------	0.1580	------	0.1950
3	------	0.1390	------	0.1550
4	------	0.1210	------	0.1350
5	------	0.1060	------	0.1200
6	------	0.0960	------	0.1050

FIGURE 28



#8 - V=4.88 '/s
#7-V=3.56'/s and #1 LW-V=3.68'/s
#1-V=3.68'/s
#4-V=3.42'/s
#6-V=1.86'/s
#3-V=1.80'/s
#2-V=1.49'/s
.25
.20
.15
.10
.05
0
1
2
3
4
5
6
NUMBER OF REBOUND
DURATION OF NEGATIVE WAVE IN SECONDS



1.00
.90
.80
.70
.60
1.25
1.75
2.25
2.75
3.25
3.75
First Rebound
All Other Rebounds
REBOUND COEFFICIENT — C
VELOCITY IN FEET/SECOND
□ – #1 L.W.
○ – #1, #2, #3, #4.

FIGURE 29

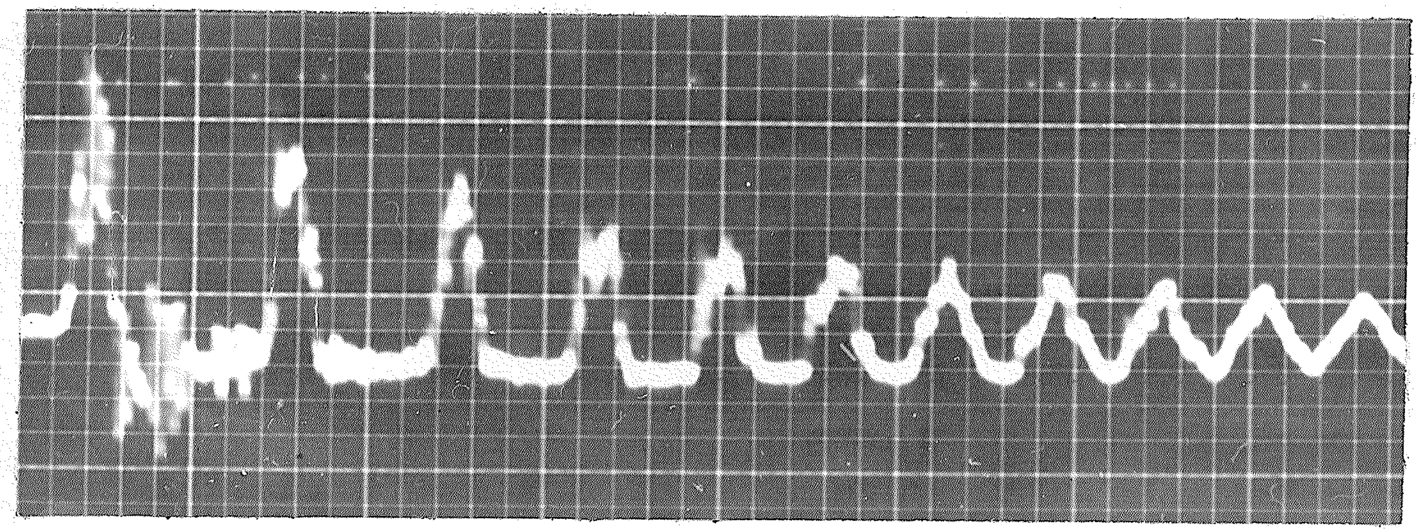


Figure 30: Film no. 3 V = 1.80 ft/sec. Divisions: Horz. 1/50 sec., Vert. 21.8 psi.

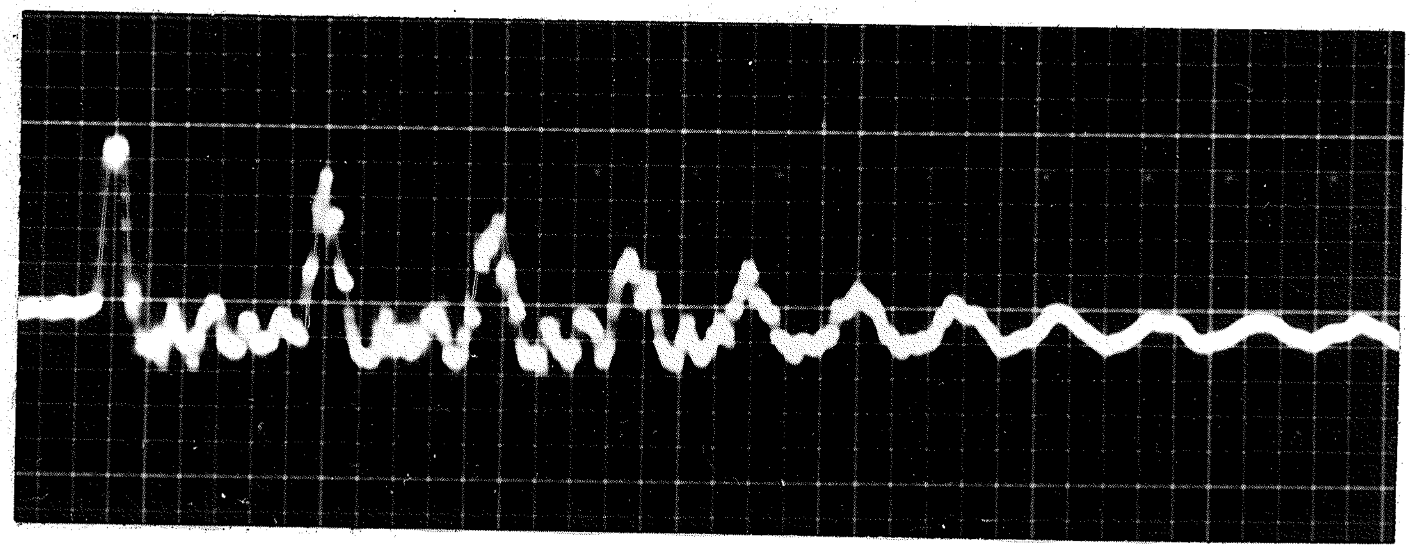


Figure 31: Film no. 6 V = 1.86 ft/sec. Divisions: Horz. 1/50 sec., Vert. 21.8 psi.

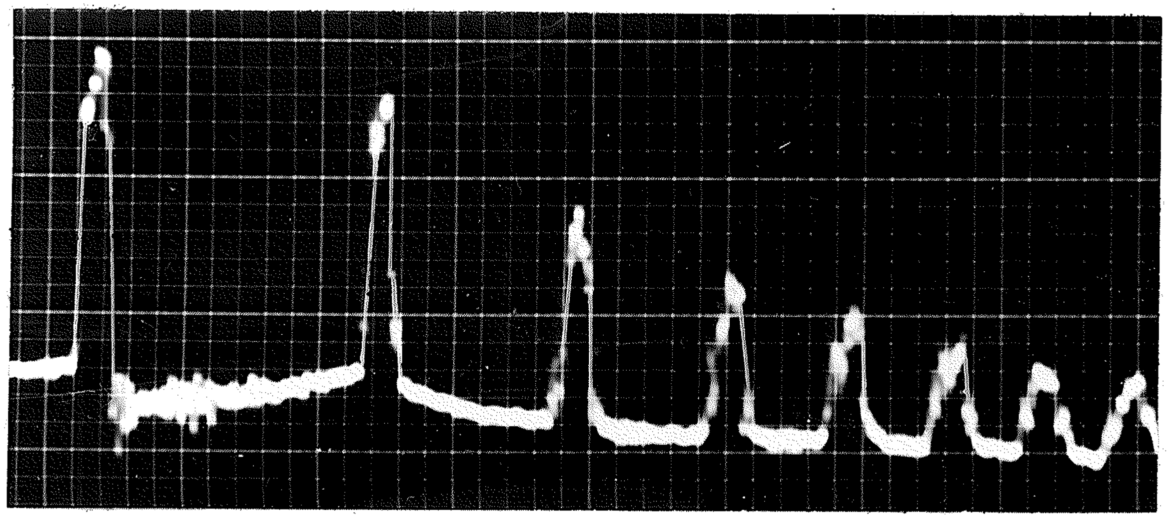


Figure 32: Film no. 1 V = 3.68 ft/sec. Divisions: Horz. 1/50 sec., Vert. 21.8 psi.

Figure 33: Film no. 7 V = 3.56 ft/sec. Divisions: Horz. 1/50 sec., Vert. 22.8 psi.

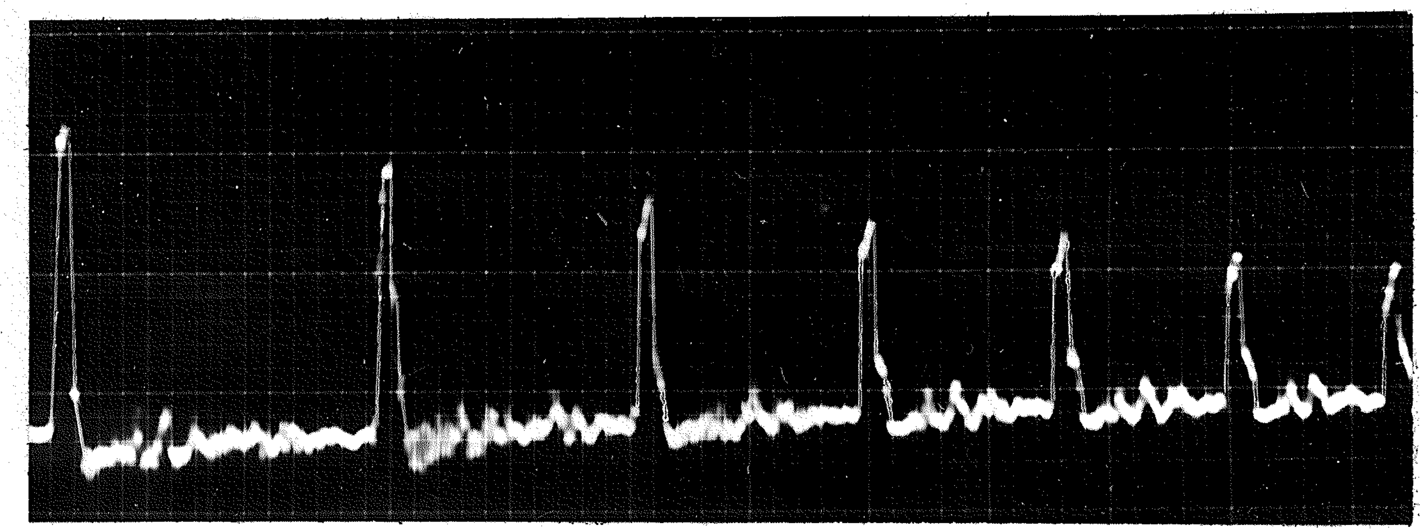


Figure 34: Film no. 8 V = 4.88 ft/sec. Divisions: Horz. 1/50 sec., Vert. 21.8 psi.

2 <u>Sample Calculations</u>

a) Calibration of the pressure cell

Given: C-10 gauges - resistance 1000 ohms
- gauge factor 3.25

Brass pressure cell - $E = 12 \times 10^6$ psi.
$\mu = 0.25$

Deflection - <u>3.7</u> divisions per 20 psi.

Theoretical output of the pressure cell-

For an internal pressure of 25 psi. the

$$\text{Longitudinal stress} = \frac{PD}{2t} = \frac{25 \times .5625}{2 \times .010} = 703.0 \text{ psi.} = S_1$$

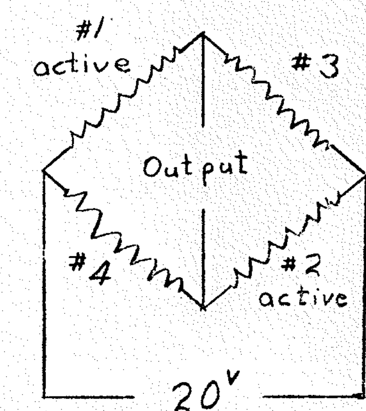
$$\text{Lateral stress} = \frac{PD}{4t} = \frac{25 \times .5625}{4 \times .010} = 351.5 \text{ psi.} = S_2$$

$$\epsilon = \frac{S_1}{E} - \mu \frac{S_2}{E}$$

$$= \frac{703.0}{12 \times 10^6} - 0.25 \times \frac{351.5}{12 \times 10^6}$$

$$= 58.58 \times 10^{-6} - 7.32 \times 10^{-6}$$

$$= 51.26 \times 10^{-6} \text{ in-in}$$



$$\frac{\Delta R}{1000} = 3.25 \times 51.26 \times 10^{-6}$$

$\Delta R = 0.1665$ ohms where ΔR = the change in resistance in one active gauge

$$\text{Output} = E \times \frac{(R_1 R_2 - R_3 R_4)}{(R_1 + R_3)(R_2 + R_4)}$$

$$= 20 \times \frac{(1000.1665 \times 1000.1665) - (1000 \times 1000)}{(2000.1665)(2000.1665)}$$

$$= \underline{1.665} \text{ mv.}$$

Actual output of the pressure cell-

20 psi. = 3.7 divisions deflection

25 psi. = 4.62 divisions

= 1.15 mv. (1mv. signal = 4 divisions)

Actual output = 1.15 mv.

$$\text{Sensitivity} = \frac{\text{actual output}}{\text{theoretical output}}$$

$$= \frac{1.15}{1.665}$$

$$= 0.698$$

b) Velocity and period of the pressure wave

Given: diameter of the pipe - 2.067 in.
thickness of the pipe - 0.154 in.
area of the pipe - 0.0234 sq. ft.
length of the pipe - 54.7 ft.
$E = 30 \times 10^6$ psi.
$k = 300,000$ psi.

$$a = \frac{12}{\sqrt{\frac{62.4}{32.2}\left(\frac{1}{300,000} + \frac{2.067}{.154 \times 30 \times 10^6}\right)}}$$

$$= \frac{12}{\sqrt{7.31 \times 10^{-6}}}$$

$$= \frac{12}{2.69 \times 10^{-3}}$$

$$= \underline{4460} \text{ ft./ sec.}$$

$$\text{Period of the pipe} = \frac{2L}{a} = \frac{2 \times 54.7}{4460} = \underline{0.0246} \text{ seconds}$$

c) Calculations for pressure wave on film no. 1

Given: Discharge = 0.0861 cfs.
Velocity = 3.68 ft/sec.
H_o = 27.4 ft.
H_a = 34.0 ft.
1mv. signal = 10.5 divisions.

Pressure from the discharge:

$$\Delta h = \frac{\Delta V}{g} \times a$$

$$= \frac{3.68}{32.2} \times 4460$$

$$= 510 \text{ ft.} = \underline{221} \text{ psi.}$$

Pressure from the curve:

Height of the first positive wave = 100 divisions

$$\text{Output} = \frac{100}{10.5} = 9.51 \text{ mv.}$$

$$h = 9.51 \times 22.9$$

(1.15 mv. = 25psi. for input of 20 volts. Actual input 19 volts.)

$$= \underline{218} \text{ psi.}$$

Wood's R value:

$$R = \frac{H_o + H_a}{H_R}$$

$$= \frac{27.4 + 34.0}{510}$$

$$= \underline{0.12}$$

Le Conte's wave spacing and pressures of the positive waves:

$$V' = \sqrt{\frac{2g(h_o + h_a)}{(1 + f(L/d)}} = \sqrt{\frac{64.4(27.4 + 34.0)}{1 + .0316\ (54.7/0.172)}} = 18.85$$

$$V'' = \sqrt{\frac{2g(h_o + h_a)}{f\ (L/d)}} = \sqrt{\frac{64.4(27.4 + 34.0)}{.0316\ (54.7/.172)}} = 19.78$$

f = 0.0316 and is assumed to remain constant.

$$n = \frac{1}{2}\left(\frac{V''}{V'}\right)^2 = \frac{1}{2}\left(\frac{19.78}{18.85}\right)^2 = 0.55$$

Phase 1: $V_o = 0.91 \times 3.68 = 3.34$ ft/sec. $\qquad C = 0.91$

$$t' = \frac{L\ V''}{g(h_o + h_a)} \tan^{-1} \frac{V_o}{V''}$$

$$= \frac{54.7 \times 19.78}{32.2(61.4)} \tan^{-1} \frac{3.34}{19.78}$$

$$= 0.548 \times 0.167$$

$= \underline{0.0915}$ seconds.

$$\text{Cosh}\ \frac{g(h_o + h_a)}{L\ V'}\ t_2 = \left[1 + \left(\frac{V_o}{V''}\right)^2\right]^n$$

$$\text{Cosh}\ \frac{32.2(61.4)}{54.7\ \ 18.85}\ t_2 = \left[1 + \left(\frac{3.34}{19.78}\right)^2\right]^{.55}$$

$$\text{Cosh}\ 1.915\ t_2 = 1.0152$$

$$1.915\ t_2 = 0.1741$$

$t_2 = \underline{0.0911}$ seconds

Duration of the negative wave = $t' + t_2$ = $\underline{0.1826}$ seconds

---

$$\text{Velocity of approach} = V' \tanh \frac{g(h_o + h_a)}{L\ V'}\ t_2$$

$$= 18.85 \tanh \frac{32.2(61.4)}{54.7 \times 18.85} \times .0911$$

$$= 18.85 \tanh 1.915 \times .0911$$

$$= 18.85 \times 0.17236$$

$= 3.25$ ft/sec.

Pressure for second peak: From approach velocity $\Delta h = \frac{\Delta V}{g} \times a$

$$\Delta h = \frac{3.25}{32.2} \times 4460$$

$$= 451 \text{ ft.}$$

$$= \underline{196} \text{ psi.}$$

From the curve - output $= \frac{90}{10.5} = 8.57$ mv.

$$\Delta h = 8.57 \times 22.9 = \underline{196} \text{ psi.}$$

Phase 2: $V_o = 0.70 \times 3.25 = 2.27$ ft/sec. $C = 0.70$

$$t' = 0.548 \tan^{-1} \frac{2.27}{19.78}$$

$$= 0.548 \times 0.1129$$

$$= \underline{0.0620} \text{ seconds}$$

$$\text{Cosh } 1.915\, t_2 = 1.0072$$

$$1.915\, t_2 = 0.120$$

$$t_2 = \underline{0.0627} \text{ seconds}$$

Duration of the negative wave $= .0620 + .0627 = \underline{0.1247}$ seconds.

Velocity of approach $= 18.85 \tanh 1.915 \times .0627$

$$= 18.85 \times .11943$$

$$= 2.26 \text{ ft/sec.}$$

Pressure for third peak: From approach velocity $\Delta h = \frac{\Delta V}{g} \times a$

$$\Delta h = \frac{2.26}{32.2} \times 4460$$

$$= 312 \text{ ft.}$$

$$= \underline{136} \text{ psi.}$$

From the curve: Output = $\frac{65}{10.5} = 6.19$ mv.

$\Delta h = 6.19 \times 22.9 = \underline{141}$ psi.

Phase 3: $V_o = 0.70 \times 2.26 = 1.58$ ft/sec. $C = 0.70$

$t' = 0.548 \tan^{-1} \frac{1.58}{19.78}$

$= 0.548 \times 0.0797$

$= \underline{0.0437}$ seconds

$\cosh 1.915\, t_2 = 1.0035$

$1.915\, t_2 = 0.0833$

$t_2 = \underline{0.0435}$ seconds

Duration of the negative wave = $.0437 + .0435 = \underline{0.0872}$ seconds.

Velocity of approach = $18.85 \tanh 1.915 \times .0435$

$= 18.85 \times .08314$

$= 1.57$ ft/sec.

Pressure for fourth peak:

From approach velocity $\Delta h = \frac{\Delta V}{g} \times a$

$\Delta h = \frac{1.57}{32.2} \times 4460$

$= 218$ ft.

$= \underline{95}$ psi.

From the curve - Output = $\frac{50}{10.5} = 4.76$ mv.

$\Delta h = 4.76 \times 22.9 = \underline{109}$ psi

Phase 4: $V_o = 0.70 \times 1.57 = 1.10$ ft/sec. C= 0.70

$t' = 0.548 \tan^{-1} \frac{1.10}{19.78}$

$= 0.548 \times 0.0556$

$= \underline{0.0304}$ seconds.

$\cosh 1.915\ t_2 = 1.0017$

$1.915\ t_2 = 0.058$

$t_2 = \underline{0.0303}$ seconds

Duration of the negative wave = .0304 + .0303 = 0.0607 seconds.

Velocity of approach = 18.85 tanh 1.915 X .0303

= 18.85 X .05796

= 1.09 ft/sec.

Pressure for fifth peak:

From approach velocity $\Delta h = \frac{\Delta V}{g} \times a$

$\Delta h = \frac{1.09}{32.2} \times 4460$

= 151 ft.

= $\underline{65.5}$ psi.

From the curve - Output = $\frac{37.5}{10.5}$ = 3.57 mv.

$\Delta h = 3.57 \times 22.9 = \underline{82}$ psi.

Phase 5: $V_o = 0.70 \times 1.09 = 0.763$ ft/sec. C = 0.70

$t' = 0.548 \tan^{-1} \frac{0.763}{19.78}$

$= 0.548 \times 0.0386$

$= \underline{0.0211}$ seconds

$$\cosh 1.915\, t_2 = 1.00082$$

$$1.915\, t_2 = 0.0404$$

$$t_2 = \underline{0.0211} \text{ seconds}$$

Duration of the negative wave = $.0211 \not{+} .0211 = \underline{0.0422}$ sec.

CHAPTER V

DISCUSSION

1 The First Positive Pressure Wave:

In all, ten different pressure waves were photographed and each of these ten were photographed three times. This gave thirty sets of waves which could be studied pertaining to valve closure. In all cases, except for film number 1 LW, the period for the first positive wave was 2L/a seconds.

In all thirty cases the pressure of the first positive wave agreed within 0.5 - 4.5% of the pressure calculated theoretically from the discharge. The normal variation was actually only about 1%. This seems to point out the validity of the equation $\Delta h = \frac{\Delta V}{g} \times a$. The fact that these pressures agree also seems to indicate that valve closure was achieved in a period of time less than 2L/a seconds.

2 Possible Sources of Error:

The calculation of the velocity of the pressure wave (a) was subject to a small error due to elongation of the pipe. It will be noted that the formula derived for the velocity of the pressure wave takes into consideration compression of the water and lateral expansion of the pipe. The pipe used for these tests was also free to expand longitudinally. It was considered that this effect would be fairly small in comparison to the other two mentioned. effects. This assumption appears to have been justified in view of the close agreement in the theoretical and actual values of the period of the pipe (2L/a).

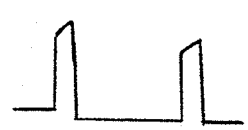
A second source of error which caused considerable trouble was a high frequency wave set up by the mechanical vibration of the pipe. This mechanical vibration was caused mainly by the shock of the gate against the valve seat. A somewhat minor source of vibration was the blow of the water hammer itself. This vibration was a fairly high frequency wave (approximately 400 cycles/second) compared to the water hammer wave (40 cycles/second). The vibration of the pipe line actually caused a stress of about 40 pounds per square inch in the pressure cell. This high frequency wave was superimposed on the water hammer pressure wave. The high frequency wave was photographed by closing the valve with no water in the pipe.

Fortunately this high frequency wave was of very short duration and affected only the first positive and negative pressures at the very most. The vibration actually built up to a peak and then died out in about a sixth of a second. The peak was very large compared to most of the wave. This meant that its effect on the water hammer wave was not as serious as might be expected.

The effect of this mechanical vibration, when the pressure cell was at the mid-point of the pipe line, was negligible. It will be noted how smooth the first positive waves were when the cell was at the mid-point and how jagged they were when the cell was at the gate. This effect was due entirely to the superimposed high frequency wave.

3 <u>Time Lag and the Pressure Build-up</u>:

An inspection of each of the positive waves will reveal that the pressure rises fairly rapidly and then increases at a much slower rate right up to the point when the pressure suddenly drops. This gives each wave the appearance shown.



There are two possible explanations of this effect. The first is that it is the result of a time lag. The pressure suddenly increases in the pipe line and the immediate effect occurs as shown by the steep part of the wave. Once this initial effect has occurred there is a more sluggish response to the increase in pressure resulting in the gentle slope on the top of the wave.

The second explanation is that the first sharp rise occurs when the velocity of the water right at the gate is checked. Now as water farther from the gate is stopped it actually results in a higher pressure than occurred at the gate. The reason for this is that the friction loss is smaller up to this point than up to the gate.. Consequently this higher pressure compresses the water between it and the gate and increases its pressure.

The second explanation appears to be a more certain explanation but it is questionable whether this explanation could account for so large a pressure build-up. Also this explanation would only cause a pressure build-up for a period of time equal to half the duration of the positive wave i.e. until the entire column of water has been stopped. Therefore it seems to be quite safe to say that the pressure build-up is a combination of the two explanations, rather than one or the other exclusively.

The pressure build-up appears to be reflected to the negative wave as shown to the right.

4 Negative Waves Recorded at the Mid-point

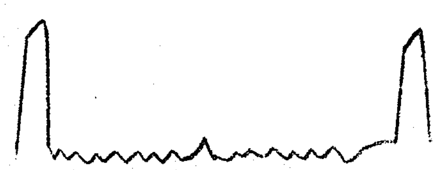
An inspection of the negative waves recorded at the mid-point of the pipe line reveals that they do not follow the expected pattern even remotely. The negative waves are a series of small pressure rises and drops giving them a saw-tooth appearance. This is most unusual because the negative waves recorded at the gate appear quite smooth.

One possible explanation of this is that the water column did not hold together during the negative wave, Subjected to an almost absolute vacuum a large quantity of air would also come out of solution to form an emulsion. As the water column moved away from the valve the pressure at the cell would vary as water and air bubbles passed the cell. Thus the water column is not subjected to a uniform pressure during the negative wave. It would be expected that this is definitely what actually occurs in a pipe line under these conditions.

The reason that the negative waves were smooth at the valve was because the water column actually pulls away from the valve and leaves a vacuum at the gate. Thus the pressure cell would not be subjected to any of the air bubble condition which existed at the mid-point.

There does appear to be a remarked similarity between the jagged peaks recorded for each of the three sets of waves at any one pressure. This seems to indicate that these peaks follow some pattern and are not of just a random nature. The exlanation previously given would indicate a quite random shape and occurence of these peaks.

There appears to be a kind of step near the end of several of the negative waves as if the column had stabalized itself and was behaving as would be expected theoretically.



These steps do not occur too often and are not very large .

5 The Coefficient of Rebound:

The variation of the coefficient as shown in figure 29 seems to agree with that stated by Le Conte. As the velocity increases the coefficient decreases very rapidly at first and then the decrease becomes very small. The results avaliable for this thesis are quite sketchy and any statement regarding the variation of the coefficient must be regarded as very general.

The coefficients were almost exclusively lower than those obtained by Le Conte. It is quite clear though that this coefficient must be affected by the rigidity of the gate. The type of gate used by Le Conte was of the plug type and therefore would be quite firm once it was dropped into place. The gate used for the tests for this thesis however was a disc type with a certain amount of play in the seat. The coefficient of rebound would be expected to be lower for this type of gate.

The coefficient remained quite predictable during the early tests, but became eratic during later tests. The first evidence of this was in wave 1 LW. These coefficients are plotted in figure 29 and as will be seen are quite high compared to the other coefficients. The coefficients for wave 1 LW are of the order of those stated by Le Conte. The force of the valve striking its seat probably damaged the edge of the disc sufficiently that it began to stick in its seat. This would improve the rigidity of the gate and thus improve its rebound characteristics.

The first coefficient in all cases is higher than the rest of the coefficients for that particular wave. The coefficients are all nearly constant except for the first value. A possible explanation for these coefficients being smaller would be the air cushioning caused by all the air which came out of solution during the negative wave. The water column is solid water during the first rebound but it is actually an emulsion during each succeding rebound.

6 <u>Durations of the Negative Waves</u>:

The results presented by Le Conte for the calculated and actual durations of the negative waves agreed very closely. The results obtained for this thesis do not present such a strong verification of the theory. They do, however, show that Le Conte's theory very closely parallels what occurs in actual practise.

It is interesting to note that in all five calculated waves the theoretical times begin to decrease too rapidly. This would mean that the coefficient of rebound should actually be increased slightly as the wave is dying out. It should be remembered however that this method of calculating times, for the negative waves, is subject to an accumulative error. It is possible that if the coefficient of rebound had been taken to one more decimal place (eg. 0.785 instead of 0.78) the deviation of results, near the end of each wave, would not have occurred.

The problem of calculating the durations of the negative waves is not cut and dried. There appear to be many variables involved which cannot be estimated. A study of the three sets of waves for each pressure shows that the durations do not remain constant. The shape of each wave remains practically the same but their spacing seems to vary a small amount. The one inconsistent factor which may be the root of all this variation is the amount of air bubbles present in the water. Care was taken to allow the water to run for a sufficient length of time to drain off all the emulsion left from the previous closure. There was no method by which the amount of air coming out of solution could be controlled.

A comparison of the durations for waves recorded at the gate and at the mid-point for the same velocity indicates that the results of films 3 and6 and also films 1 LW and 7 agree very closely. The fact that the results of film 7 agree with 1 LW indicates that once more the valve appears to have been more rigid. The results of film 8 cannot be compared with those of a closure at the gate except to note that in figure 28 it follows the general slope of the curves for films 1 , 2 , 3 etc.

7 Pressures of the Positive Waves:

In the discussion of section 1 it was stated that the actual pressures of the first positive waves agreed very closely with the theoretical values. A furthur comparison was made by calculating the theoretical pressures which should occur knowing the new velocities of approach after each negative wave. The results are recorded in table 3. The pressures for films 1 , 1 LW, 3 and 4 agree very closely with the actual pressures, while those of film 2 are in error by 20 - 25%. The results of films 3 and 6 oncemore agree very closely. The results of film 7 do not appear to follow either film 1 or 1 LW. This is very strange because the agreement of films 7 and 1 LW, as far as durations of negative waves was concerned, was very good. Film 8 oncemore seems to fit the general pattern of films 1 , 2 , 3 etc.

8 Wood's Theory:

A comparison of the pressure waves obtained for various R values with those shown in figure 15 on page 19, indicate no similarity whatsoever.

This graphical method of analysis seems to give theoretical results which are not even approached in practise. There are several instances where Wood's method results in the highest pressure being attained during the third or fourth positive wave. This condition was not found to exist in even one single case. A test was even run at an R ratio of 0.45 which should result in a maximum pressure 3.5 times the pressure of the first positive pressure wave. The wave followed the general pattern of all the pressure waves and had almost died out by the fourth positive wave.

The peaks of the positive waves in many cases have a slightly ragged appearance. This could tie-in with Wood's theory as the general shape and location of these changes in pressure do agree with the waves shown in figure 15 on several occassions. It should be noted however that in the majority of cases there is no comparison and also the pressure drops do not even approach Wood's theoretical values in magnitude.

CHAPTER V1

CONCLUSIONS AND RECOMMENDATIONS

1 Conclusions:

a) The general equations of water hammer have been verified within experimental accuracy.

b) The water column does not hold together when the pressure drops to absolute zero during the negative wave.

c) The wave form of the negative wave at the mid-point of the pipe does not occur as expected theoretically.

d) In general, the coefficient of rebound decreases with an increase in velocity. For any set of waves the coefficient of rebound for the first rebound is greater than that for each succeeding rebound. The coefficient is almost a constant for all but the first rebound.

e) Le Conte's method of analysis gives a much closer approximation of actual conditions than does Wood's graphical method.

2 Recommendations:

a) A great deal of work could be carried out at lower pressures if the mechanical

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