



Analysis of hydraulic transients in an injection device for two-phase flow systems
by Gary Allen Hendrix

A thesis submitted to the Graduate Faculty in partial fulfillment of the requirements for the degree of
MASTER OF SCIENCE in Civil Engineering
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Abstract:

A method is presented for designing the operating rates of seven valves in a system that injects a mixture of solids and water into a high pressure pipeline without inducing hydraulic transients in that pipeline. Hydraulic transients are generated within the injection system itself, however, and the individual valves are operated in a manner that limits the magnitude of the transients.

The method of characteristics is used to solve the two partial differential equations that describe the phenomenon of waterhammer. The resulting characteristic equations are applied to four basic design cases. These design cases are the basic components of the injection operation. Application of the characteristic equations to the basic design cases yields complete hydraulic information about the flow conditions on either side of all the valves in the system and permits the determination of the gate opening of each valve at any time.

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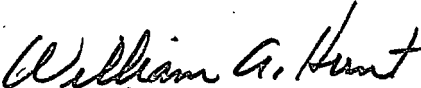
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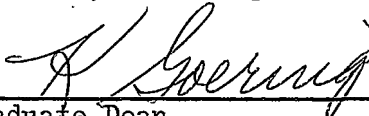
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ABSTRACT

A method is presented for designing the operating rates of seven valves in a system that injects a mixture of solids and water into a high pressure pipeline without inducing hydraulic transients in that pipeline. Hydraulic transients are generated within the injection system itself, however, and the individual valves are operated in a manner that limits the magnitude of the transients.

The method of characteristics is used to solve the two partial differential equations that describe the phenomenon of waterhammer. The resulting characteristic equations are applied to four basic design cases. These design cases are the basic components of the injection operation. Application of the characteristic equations to the basic design cases yields complete hydraulic information about the flow conditions on either side of all the valves in the system and permits the determination of the gate opening of each valve at any time.

CHAPTER I

INTRODUCTION

The hydraulic transport of solids in pipelines has generated great interest in recent years. Mining companies have made extensive use of pipelines in transporting solid materials to processing mills. The Colorado School of Mines in 1963 cited fifty-two examples of such transport in a book (8)^{*} concerning the most current state of the art in transport of solids in steel pipelines. The longest such pipeline in the United States is 108 miles long and is used by the Consolidation Coal Company to transport coal slurries.

The success of pumping solids by mining companies caused pulp mills to consider the possibility of reducing trees to wood chips at harvesting areas and pipelining the chips to the mills in place of transporting the trees by truck or railroad. As a result, the Pulp and Paper Institute of Canada and the Civil Engineering Department of Queen's University in Kingston, Ontario began investigations of the hydraulic feasibility of transporting wood chips in a pipeline.

The hydraulic transport of wood chips offers more problems than those encountered by mining companies in pipelining slurries. Wood chips are large and irregular in size and shape whereas slurries are mixtures of water and finely ground solids. One of the major problems is passing wood chips through pumps. The sizes of the chips rules out the use of positive displacement pumps due to the problems incurred at intake and

^{*} Numbers in parentheses refer to numbered references in the Literature Cited.

exhaust ports and damage to the chips. The only useable centrifugal pumps commercially available are low head trash pumps which can pass solids, but are rather inefficient in converting input energy to flow energy. Economic spacing of pumping stations on a fully operational pipeline requires that relatively high pressures be developed at each pumping station. The high operating pressure is theoretically attainable if trash pumps are placed in series but the casings and packing in these pumps are not designed for the high pressure operation that some of the pumps would experience.

An alternative to the series of staged pumps is to introduce the solids into the flow without passing them through pumps. A system of pumps and valve was patented by Consolidation Coal Company requiring the chips to pass through only one low head pump (see Figure 1). This system continually injects wood chips into the main pipeline by alternating wood chip flow into the main pipeline from two injection lines. The low pressure pump pumps a wood chip, water mixture into one pipe at low pressure. A high pressure pump, pumping clear water, forces the mixture from a previously charged pipe of the same length into the main pipeline. When the pipe injecting wood chips into the main pipeline becomes completely filled with clear water, switching valves divert the flow such that the pipe, now filled with clear water, feeds the intake of the high pressure pump as wood chips from the low pressure pump fill this line from the opposite end. The pipe, now filled with chips, begins injecting the chips into the main pipeline as clear water from the high pressure

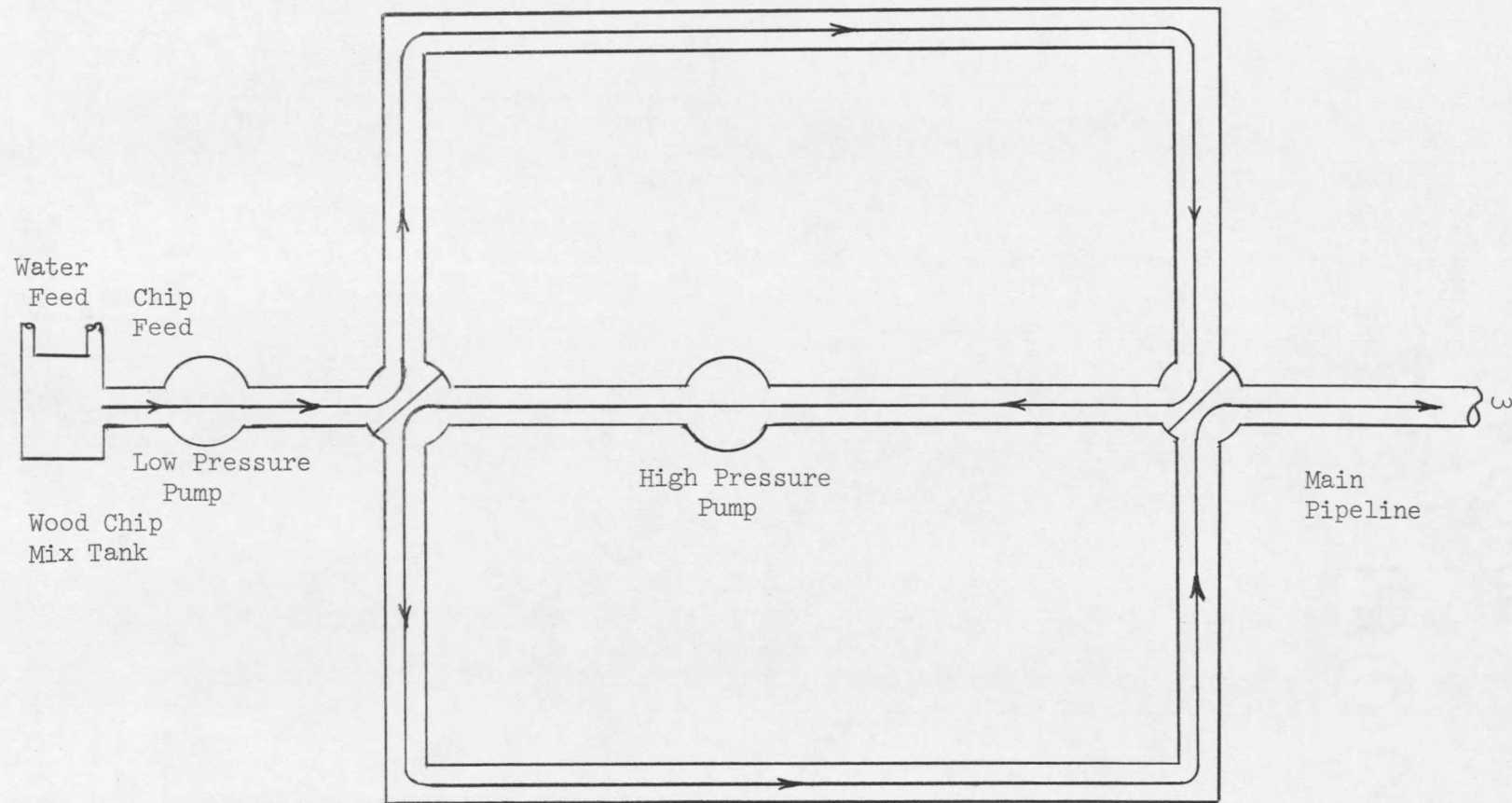


Figure 1. Proposed injection system

pump forces the chips from the line. This system, however, generated severe pressure surges when the valves were operated rapidly and was not used for any commercial operation.

This study was undertaken to determine if this injection system can be operated in a manner which would control the transients developed by the operation of the switching valves.

CHAPTER II

LITERATURE REVIEW

In order to develop a method of controlling the hydraulic transients generated by the injection system described in the preceding chapter, a basic understanding of the problem and methods of analyzing it must be obtained. Hydraulic transients are the time variance of pressure and discharge in a confined piping system and are often referred to as "waterhammer". The waterhammer phenomenon is induced by any external force on a fluid system which would change its initial steady state condition. A valve being opened or closed produces such a force.

As a valve is closed, pressure waves in excess of the operating pressure in the pipe are sent upstream to destroy the momentum of the incoming fluid. These pressure waves travel at a characteristic speed which depends on the physical properties of the fluid and the conduit in which it is flowing. When these positive pressure waves reach the upstream boundary of the pipe, they are reflected back to the valve as negative waves. The magnitude of the negative waves is slightly smaller than that of the positive waves due to frictional damping of the positive waves as they travel up the pipe. As the negative waves return to the valve they interact with positive waves which are still being generated at the valve. The net effect of the negative reflected waves is to modify the pressure increases due to the positive waves generated at the valve. If the valve is closed or nearly closed at the time the first negative wave returns to the valve, there will be no positive waves to interact with the negative wave and the pressure at the valve will drop

below operating pressure. In extreme cases the pressure will drop low enough to initiate cavitation. Low pressure waves, lower than operating pressure, are then sent upstream, inverted at the reservoir and returned to the valve. At the valve another series of pressure waves greater than the normal operating pressure will be sent upstream as the reflected negative waves return to the valve. The effect is to produce a sinusoidal pressure fluctuation at every point in the pipe. The frequency of the pressure fluctuation is $a/4L$ where L is the pipe length and a is the wave velocity. The changes in pressure are accompanied by reversals in flow direction and a hammering effect is created in the pipe. The oscillations will persist until friction damps them out. If a valve can be operated slowly enough, the magnitude of the pressure surges are negligible because the pressures are proportional to the rate at which the flow is regulated. However, during emergencies and in special cases such as that encountered in the proposed wood chip injection system, a valve may be required to close very rapidly.

According to Jaeger (3), the differential equations which describe the phenomena of waterhammer were first written in their correct form in the late 1890's by N. Joukowsky. These equations, however, are quite difficult to solve. Lorenzo Allievi is credited with making the first solution to a simplified form of the waterhammer equations (3). Allievi formulated an algebraic solution to the equations which are:

$$V_t = g H_x \quad (1)$$

and

$$\frac{a^2}{g} V_x = H_t \quad (2)$$

a is the wave velocity; g is the gravitational constant; V_x is the partial derivative of velocity with respect to distance; V_t is the partial derivative of velocity with respect to time; H_x is the partial derivative of the head with respect to distance; and H_t is the partial derivative of the head with respect to time. Because the equations in their correct form are:

$$gH_x + VV_x + V_t + \frac{fV|V|}{2D} = 0 \quad (3)$$

and

$$H_t + \frac{a^2}{g} V_x + V \sin \phi + VH_x = 0 \quad (4)$$

ϕ is the slope of the pipe, Allievi's solution is limited in the precision of its results.

Graphical methods of solving the same forms of the differential equations that Allievi used were developed in the later 1920's (5). Louis Bergeron (1) and John Parmakian (5) have written excellent references on the graphical solutions of the waterhammer equations. The principle difficulties with graphical methods are the accuracy of the answers and the time required to make a solution.

With the advent of the digital computer in the 1950's methods of solving differential equations, which before had been impractical to solve, became practical. In 1960, Mary Lister (4) presented a numerical method for solving hyperbolic differential equations, like the waterhammer equations, by the method of characteristics. The characteristic solution to a set of partial differential equations reduces these

equations to a set of ordinary differential equations which can be solved by numerical methods.

V. L. Streeter (6) applied the method of characteristics to Eqs. (3) and (4). He has obtained excellent correlation between experimental results and theoretical results for simple pipelines. Because of the availability of a computer and because of the simplicity of application of the characteristic equations to physical systems, the method of characteristics was used to study the hydraulic transients developed by the valving operation in the wood chip injection system previously described.

CHAPTER III

DEVELOPMENT OF EQUATIONS

The basic equations and methods of analysis used in determining a method of operation for the valves in the injection system are developed in this chapter. The development proceeds from the basic differential equations, through the characteristic solution to these equations, to the equations and methods of analysis used in two basic applications of the characteristic equations.

A. Basic Water Hammer Equations

The basic differential equations which describe transient flow in a closed conduit in a two-dimensional plane are given by the equation of motion and the equation of continuity, Eqs. (3) and (4). The forms of these equations adopted for this analysis are

$$gH_x + V_t + \frac{fV|V|}{2D} = 0 \quad (5)$$

and

$$H_t + \frac{a^2}{g} V_x = 0 \quad (6)$$

Rather than discuss the development of the basic equations and their simplified forms in this paper, the reader is referred to the development by Streeter (6).

B. Solution by Method of Characteristics

The method of characteristics provides a powerful method of solving sets of linear partial differential equations. This method, outlined

briefly below, converts the partial differential equations to ordinary differential equations which describe the action of the dependent variables along given characteristic directions in the independent variable plane. The reader is referred to the discussion of Mary Lister (4) and S. H. Crandall (2) for the details of the mathematical analysis of the method of characteristics. The method of characteristics is applied to Eqs. (5) and (6) in the following paragraphs.

Eqs. (5) and (6) can be combined linearly by using an unknown multiplier, Z . If Eq. (6) is multiplied by Z and added to Eq. (5), the result, after rearrangement of terms, is:

$$\left(\frac{g}{Z} H_x + H_t\right) + \left(\frac{Z a^2}{g} V_x + V_t\right) + \frac{fV|V|}{2D} = 0 \quad (7)$$

The method of characteristics involves the selection of two values of Z that result in converting Eqs. (5) and (6) into a pair of total differential equations. Any two real, distinct values of Z will yield two equations in terms of H and V that are equivalent in every respect to Eqs. (5) and (6). If V and H are functions of x and t only, their total derivatives are:

$$\frac{dH}{dt} = H_x \frac{dx}{dt} + H_t \quad (8)$$

and

$$\frac{dV}{dt} = V_x \frac{dx}{dt} + V_t \quad (9)$$

Examination of Eq. (7) shows that if

$$\frac{dx}{dt} = \frac{g}{Z} \quad (10a)$$

and if

$$\frac{dx}{dt} = \frac{Z a^2}{g} \quad (10b)$$

Eq. (7) becomes an ordinary differential equation:

$$Z \frac{dH}{dt} + \frac{dV}{dt} + \frac{fV|V|}{2D} = 0 \quad (11)$$

Solving Eqs. (10a) and (10b) yields two particular values of Z which reduce the original equations to the ordinary differential equation given by Eq. (11). The solutions are:

$$Z = \frac{+g}{a} \quad (12)$$

Substituting these values into Eqs. (10a) and (10b) yields:

$$\frac{dx}{dt} = \frac{+a}{1} \quad (13)$$

Eq. (11) will satisfy Eqs. (5) and (6) only when Eq. (13) is satisfied.

Thus there are two characteristic directions in the x - t plane along which Eq. (11) is applicable.

For the positive characteristic direction

$$C^+ = \frac{dx}{dt} = a \quad (14)$$

Eq. (11) becomes

$$g \frac{dH}{dt} + \frac{dV}{dt} + \frac{fV|V|}{2D} = 0 \quad (15)$$

For the negative characteristic direction

$$C^- = \frac{dx}{dt} = -a \quad (16)$$

Eq. (11) becomes

$$-\frac{g}{a} \frac{dH}{dt} + \frac{dV}{dt} + \frac{fV|V|}{2D} = 0 \quad (17)$$

Eqs. (15) and (17) are applicable only along the characteristic directions given by Eqs. (14) and (16). These characteristic directions are illustrated on the x - t diagram shown in Figure 2.

The ordinary differential Eqs. (15) and (17) are not amenable to an

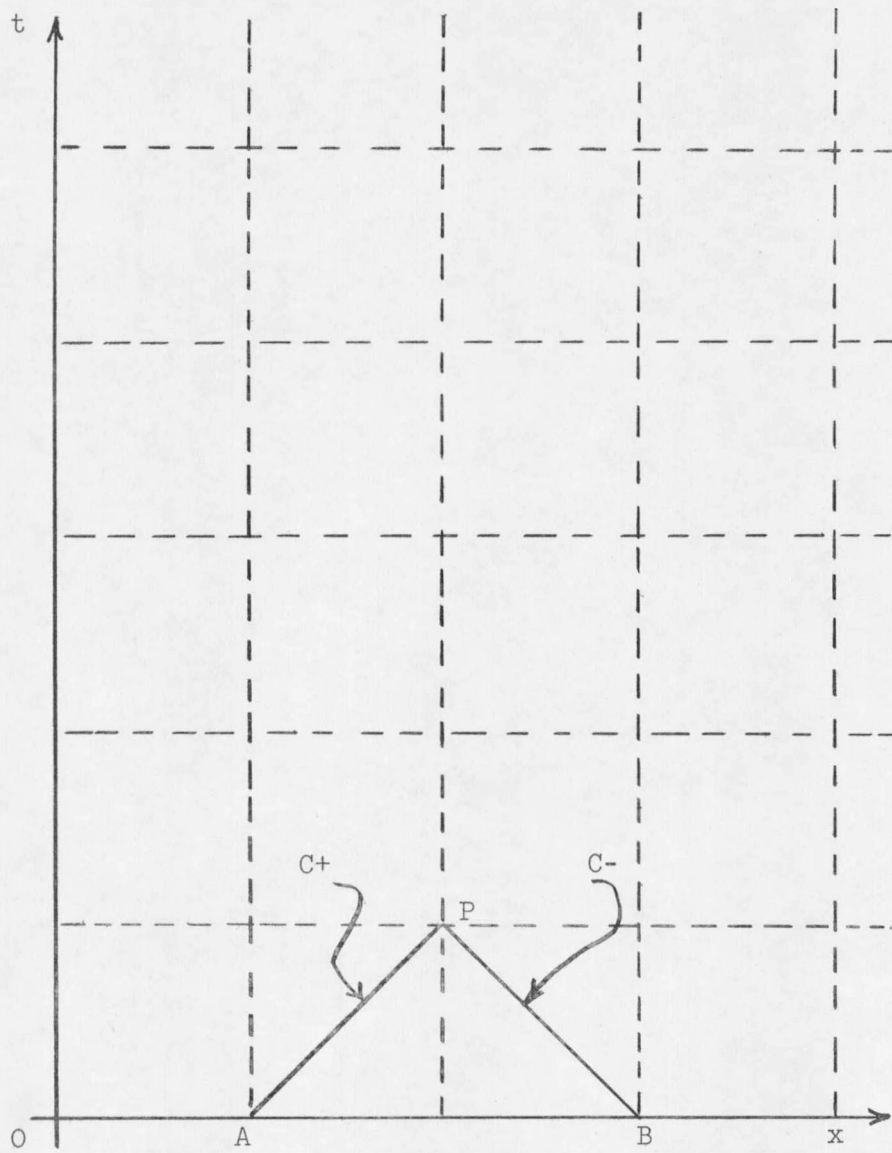


Figure 2. Characteristics in the x - t plane

exact mathematical solution, but may be solved by finite difference techniques. The equation written in finite difference form for the C^+ direction is:

$$V_P - V_A + \frac{g}{a} (H_P - H_A) + \frac{fV|V|}{2D} (t_P - t_A) = 0 \quad (18)$$

and for the C^- direction is:

$$V_P - V_B - \frac{g}{a} (H_P - H_B) + \frac{fV|V|}{2D} (t_P - t_A) = 0 \quad (19)$$

The subscripting notation refers to Figure 2. With the use of the digital computer, relatively small time and distance increments can be taken on the $x-t$ plane, and a very close approximation to an exact solution can be made.

C. Application of the Method of Characteristics

The transient analysis for a pipeline of constant diameter and constant thickness is effected using Eqs. (18) and (19). The method of applying these equations to a physical system is shown in the following example. The system consisting of a single pipe with a constant head reservoir at one end and a valve at the other is shown in Figure 3. The $x-t$ diagram for this system is shown directly beneath the pipe. The grid is organized by setting $dx = L/N$ where L is the pipe length and N is an arbitrary integer. The time increment dt equals dx/a . The object is to determine the heads and velocities at all points in the grid as the valve is closed.

Initially the flow is in a steady state condition, and the heads

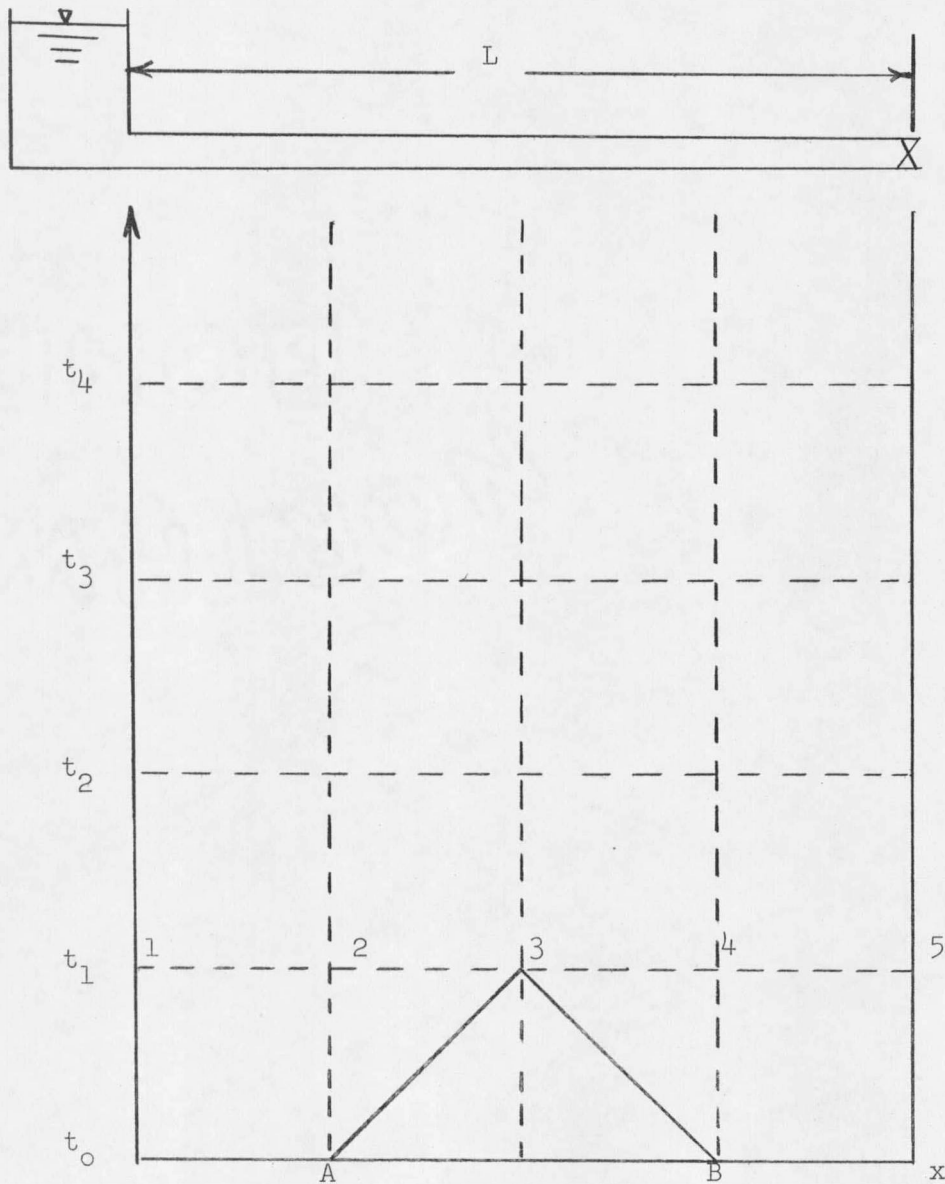


Figure 3. Application of the characteristic Equations to a simple pipeline

and velocities at all points along the pipe at time $t = t_0$ can be calculated by use of the basic energy equation of fluid flow. At time $t = t_0 + dt$ the valve is closing and a transient pressure surge is created in the pipe.

The first step in the solution is to determine the heads and velocities at the interior points 2, 3, and 4. The heads and velocities are found by simultaneously solving Eqs. (18) and (19) for both the head and velocity, because such a solution represents a solution for the head and velocity at the intersection of the two characteristic lines. The result of this simultaneous solution for velocity at point 3 is:

$$V_3 = 0.5 (V_A + V_B + \frac{g}{a} (H_A - H_B) - \frac{fdt}{2D} (V_A |V_A| + V_B |V_B|)) \quad (20)$$

For the head at point 3 it is:

$$H_3 = 0.5 (H_A + H_B + \frac{a}{g} (V_A - V_B - \frac{fdt}{2D} (V_A |V_A| - V_B |V_B|))) \quad (21)$$

The quantities H_A , H_B , V_A , and V_B are illustrated in Figure 3 and are known from the initial condition of the flow in the pipe. The quantity dt represents $t_P - t_A$ which is also $t_3 - t_B$. These equation forms can be applied to each of the interior points to find the heads and velocities at these points at time $t = t_0 + dt$.

The heads and velocities at each of the boundaries, points 1 and 5, cannot be calculated as one characteristic at each end is not available. Other boundary conditions must be specified at each end for use with the existing characteristic. The boundary condition at the reservoir end of the pipe is quite simple. The reservoir will maintain a constant head at all times, and therefore the head at this end of the pipe is constant at

the value of the reservoir head at all times if entrance losses are neglected. With the head known at point 1 and the head and velocity known at point A the negative characteristic equation, Eq. (19), can be used to determine the velocity at point 1.

This leaves the head and velocity at point 5, the valve, to be determined. This presents a slightly more complex problem than the one encountered at the reservoir because there are two unknowns. Two equations, therefore, are necessary to solve for these quantities. One equation available is the positive characteristic equation. An equation representing flow across the valve must be developed for the second equation. The equation for flow through an orifice is used to develop this second equation. The steady state orifice equation is

$$V_o A = (C_d A_g)_o \sqrt{2g \Delta H_o} \quad (22)$$

where V_o is the initial velocity; C_d is the valve coefficient; A_g is the initial area of the valve opening; and ΔH_o is the steady state head loss across the valve when it is completely open. At any time, t , during the gate travel, Eq. (22) becomes:

$$V A = C_d A_g \sqrt{2g \Delta H} \quad (23)$$

If Eq. (23) is made dimensionless, it can be written as:

$$\frac{V}{V_o} = \tau \sqrt{\frac{\Delta H}{\Delta H_o}} \quad (24)$$

where τ represents:

$$\tau = \frac{(C_d A_g)}{(C_d A_g)_o} \quad (25)$$

Eq. (23) and Eq. (17) can be solved simultaneously for the velocity at

the valve at time $t = t_0 + dt$ for a given value of . The result is:

$$V_P = \frac{-1 + \sqrt{1 + 4 \left[\frac{g H_0}{a(\tau V_0)} \right]^2 \left[V_A + \frac{g}{a} H_A - \frac{f V_B |V_B|}{2D} (t_p - t_A) \right]}}{2 \left[\frac{g H_0}{a(\tau V_0)} \right]^2} \quad (26)$$

At this point, the heads and velocities are known at all points in the pipe at time $t = t_0 + dt$. The solution can now proceed to time $t = t_0 + 2dt$, where the heads and velocities are determined in the same manner as they were at time $t = t_0 + dt$. The solution can be made at progressive time intervals until the transients are damped out, or until the person making the solution has obtained the information he desires about the transients.

D. Design of Valve Closure

Often, as is the case in this study, valves are required to open or shut as rapidly as possible without inducing severe hydraulic transients in the pipeline. The valve closure which changes the flow to another predetermined rate in the shortest possible time without exceeding a given pressure head in the system is unknown. One method of solving the problem is to use different trial valve closure rates in the analysis described in the preceding section and to check each trial to see if the limiting head is exceeded. There are an infinite number of valve closures which may be tried, and it would be impossible to tell if the fastest method of valve operation had been determined.

An alternative to the trial and error method of finding the shortest allowable valve closure time has been presented by Streeter (7). He has developed an analytical method for predicting the maximum rate of valve operation, without exceeding a given head, in a simple pipe with a reservoir at one end and a valve at the other.

Streeter's analysis divides the x - t diagram into the five flow regions marked with Roman numerals in Figure 4. Each region is described in the following sentences. Region I is an undisturbed flow bounded on top by the first disturbance wave originating from the valve. Region II is a transient flow region in which the head at the valve is increasing from its initial value to its maximum value in one round trip wave travel time, or $t = 2L/a$. In this region the flow is reorganizing from its initial state to the flow conditions in region III. The latter is a region in which the flow velocity is constant throughout the pipe at any instant of time, but the flow decelerates continuously in each succeeding time step until it reaches its final steady state velocity at point 4. In region III the head increases linearly from the reservoir to the maximum design head just upstream from the valve. Region IV is a transient region similar to region II, but the head is decreasing from its maximum value to its final, steady state value. Region V is an undisturbed region having the steady conditions behind the last disturbance wave that is reflected back to the valve.

The physical significance of these flow divisions becomes apparent if the system is viewed from the reservoir with the intent of stopping

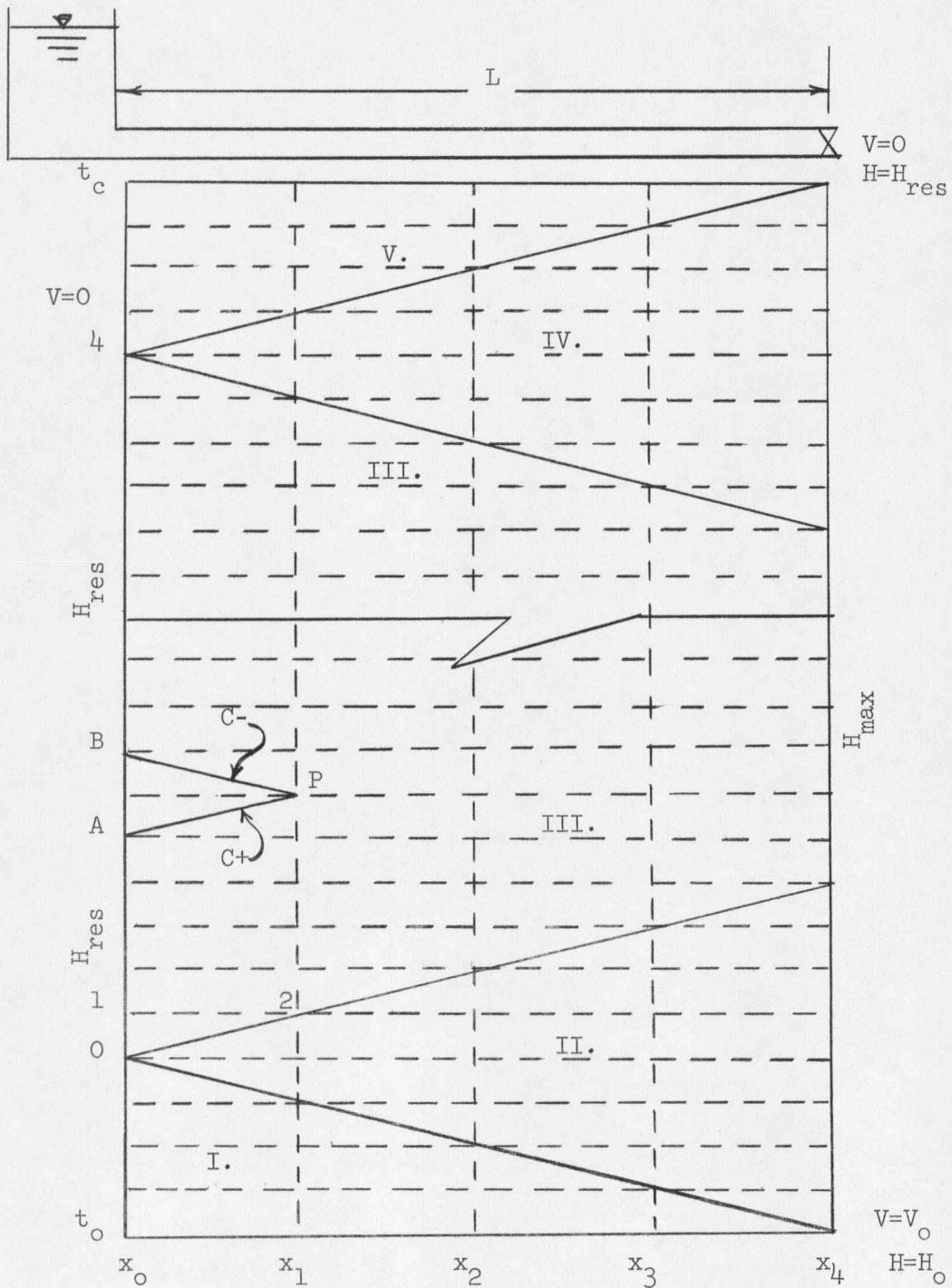


Figure 4. Design of rate of valve closure by the method of characteristics

the flow in the shortest time without exceeding a given design head. From the first movement of the valve there will be a delay of one wave travel time ($t = L/a$) before the first disturbance reaches the reservoir. After this time the reservoir is required to reduce the flow into the pipe as rapidly as possible. In order that the flow deceleration in region III be uniform at any instant of time, the head increase opposing the flow across each dx increment must be the same so that each element of water is opposed by the same resisting force. The requirement of equal head increases across each dx element is met only by a linear variation of the opposing head from the reservoir to the maximum design head. The head at point 2 in Figure 4 is equal to

$$H_2 = H_R + \frac{H_{\max} - H_R}{N} \quad (27)$$

where N is the number of pipe divisions, H_R is the reservoir head, and $H_{\max}$ is the maximum design head. The velocity at point 0 is the undisturbed, steady state velocity and the head is equal to the reservoir head. V_2 can now be determined from Eq. (18) using $H_p = H_2$. The velocity is uniform in the first pipe division at this time, therefore $V_1 = V_2$ and $H_1 = H_R$.

This method of solving for velocities at the reservoir proceeds up the time scale until the predicted velocity becomes zero or negative. The time at which the velocity is zero may not occur at an even time interval in which case the predicted velocity for that time division would be negative. This time defines the end of region III. The time at which the velocity first becomes zero must be determined by interpolation,

using the even time increments on either side of the zero point. All velocities coming into the pipe equal zero after the time corresponding to point 4 in Figure 4. At $t = L/a$ after point 4, the velocities everywhere in the pipe are zero, and the head everywhere in the pipe equals the reservoir head.

Because the initial and final heads and velocities are known at all points in the pipe as well as the heads and velocities at the reservoir, only the interior points of the x - t diagram in Figure 4 are not determined. These points are determined by applying the characteristic equations illustrated in Figure 4 by points A, B, and P. In this case Eqs. (18) and (19) are solved simultaneously to find the velocity at point P. The result of this solution is:

$$V_P = 0.5 \left(V_A + V_B + \frac{g}{a} (H_A - H_B) - \frac{f(t_P - t_A)(V_A |V_A| - V_P |V_P|)}{2D} \right) \quad (28)$$

Because V_P is on both sides of Eq. (28), a trial and error process is required to determine the velocity at point P. The head at P is found by either Eq. (18) or (19). The solution for the system proceeds by solving for the heads and velocities for all time increments at a given location in the pipe. After the heads and velocities are determined for all time increments at x_1 in Figure 4, the heads and velocities, for all time increments, are determined at location x_2 .

Finally the heads and velocities just upstream of the valve point x_4 are determined for all times. In this illustration the valve discharges into the atmosphere, and therefore the head downstream of the valve is known at all times. Because the head drop across the valve and

the flow velocity immediately upstream of the valve are known at all times, Eq. (24) can be used to determine the tau value (τ) for each time increment.

Sections C and D illustrate two basic methods of making use of the characteristic equations. These basic methods of application are used in the following chapter to determine the rate of movement (opening and/or closing) of all the valves in the injection system.

CHAPTER IV

ANALYSIS OF THE INJECTION SYSTEM

The applications of the characteristic equations developed in the previous chapter will be used to analyze the wood chip injection system. Because flow free from transients is required in the main pipeline, the injection system illustrated in Figure 1 was modified to that shown in Figure 5. An accumulator, a pipe recycling wood chips to the mixing tank, and valves 1, 4, and 7 were added to the system. The purpose of the recycling line is to prevent transients from reaching the low pressure pump. The accumulator in this system is a tank which will maintain a constant head at all times. Its purpose is to maintain a constant discharge from lines "A" and "B" and to regulate the pressures in these lines so that transients will be not allowed to reach the high pressure pump.

In order to make an analytical solution for the valve movements, the injection system must be analyzed in sections as basic flow control operations are executed. There are five principle phases of flow control for injecting the wood chips into the high pressure pipeline. These phases are illustrated by considering the operation cycle beginning as line "A" is filled with chips from the low pressure pump. First, the inflow of chips into the injection line "A" is stopped by valve 2. The second phase raises the pressure in line "A" to the pressure level required in the main line. The third phase switches the flow from the high pressure pump to line "A" and switches valve 5 to a position where the wood chips flow into the main line from line "A". The fourth phase

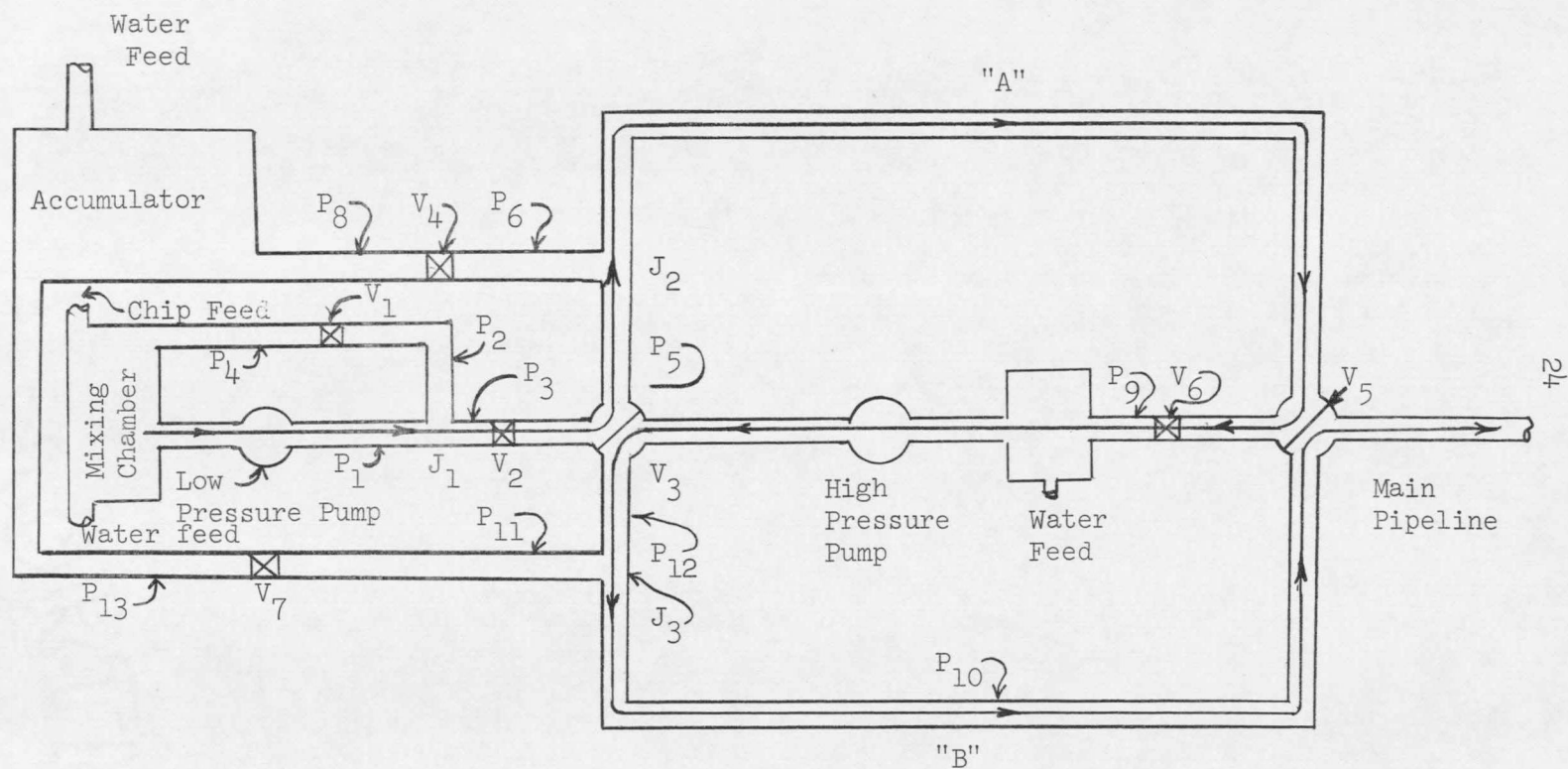


Figure 5. Modified wood chip injection system

reduces the pressure in injection line "B"; and the fifth phase opens valve 2 and starts to fill line "B" with wood chips. Phases 4 and 5 are the reverse of phases 1 and 2, and once the operation of the valves in phases 1 and 2 is determined, the operation of valves in phases 4 and 5 is also determined. Each phase has a key operation which controls the movement of all the valves in that phase.

Each of the five phases of flow control can be analyzed by one or more of four basic design applications of the characteristic equations. The basic design cases will be described. Their application to the system will then be discussed in greater detail. Computer programs have been written to execute each of the four design cases.

A. Design Case I

Design case I is described in Chapter 3, Section D. It consists of a pipe with a reservoir at one end and a valve at the other. The valve is closed as rapidly as possible without exceeding a given maximum or minimum design head at any place within the pipeline. The data generated from this design process will furnish input data to the second and third design cases.

B. Design Case II

Design case II is a special case of design case I. It consists of a simple pipeline with a reservoir at one end and a valve at the other, but instead of limiting the pressure heads in the pipe as was done in

case I, a rate of flow determined from application of one of the other design cases is input at the reservoir end of the pipe and the analysis is carried out to determine the heads and velocities at the valve.

The analysis of this case is similar to that described in the previous section. The reservoir boundary condition is known at all times because heads are constant and flows entering the pipe are given. The flow rates entering the pipe at the reservoir are determined by other design cases (I, III, IV) applied to other pipes entering the reservoir.

The energy equation can be used to solve for the heads and velocities along the pipe at time $t = t_0$ since at this time the flow is undisturbed. One wave travel time down the pipe after the flows entering the pipe become steady, the last disturbance wave will reach the valve, and the flow throughout the pipe will be steady. After this time the energy equation can be used to solve for heads and velocities throughout the pipe. The case is the same as the case described in Section D of Chapter 3, when only the interior points were undetermined. The solution then proceeds by applying Eqs. (28) and (18) to solve for the velocities and heads at the interior points.

C. Design Case III

Design case III is again a simple pipe with a reservoir at one end and a valve at the other, but instead of having a predetermined flow input at the reservoir end as was done in the previous design case, a flow is input at the valve. The object is to solve for the heads at the

valve and the velocities at the reservoir.

The initial heads and velocities are known throughout the pipe. The negative characteristic will give the velocity at the reservoir for time $t = t_0 + dt$. The positive characteristic will give the head at the valve for time $t = t_0 + dt$. The heads and velocities at the interior points, during this time increment, are determined from Eqs. (20) and (21), as illustrated in Section C of Chapter 3. At a time L/a after the flow into the pipe becomes steady, the flow throughout the pipe should be nearly steady if the input flow values at the valve came from applying design case I to a pipe with the same geometry as the pipe in question. If the input flow values came from stroking (manipulation according to the time rate of valve movement determined from design case I) a valve in a pipe of completely dissimilar dimensions, there is nothing that requires the transients in the pipe in question not to exceed a given design head because the input is in effect completely random for that pipe.

D. Design Case IV

Design case IV consists of a pipe with valves at both ends. The pressure in the pipe is to be increased without increasing the flow from the downstream end of the pipe.

In this case the heads and velocities are not known at the upstream end of the pipe, and only the velocities are known at all times at the downstream end of the pipe. Figure 6 illustrates this case. Regions I and II are undisturbed flow regions, and hence, heads and

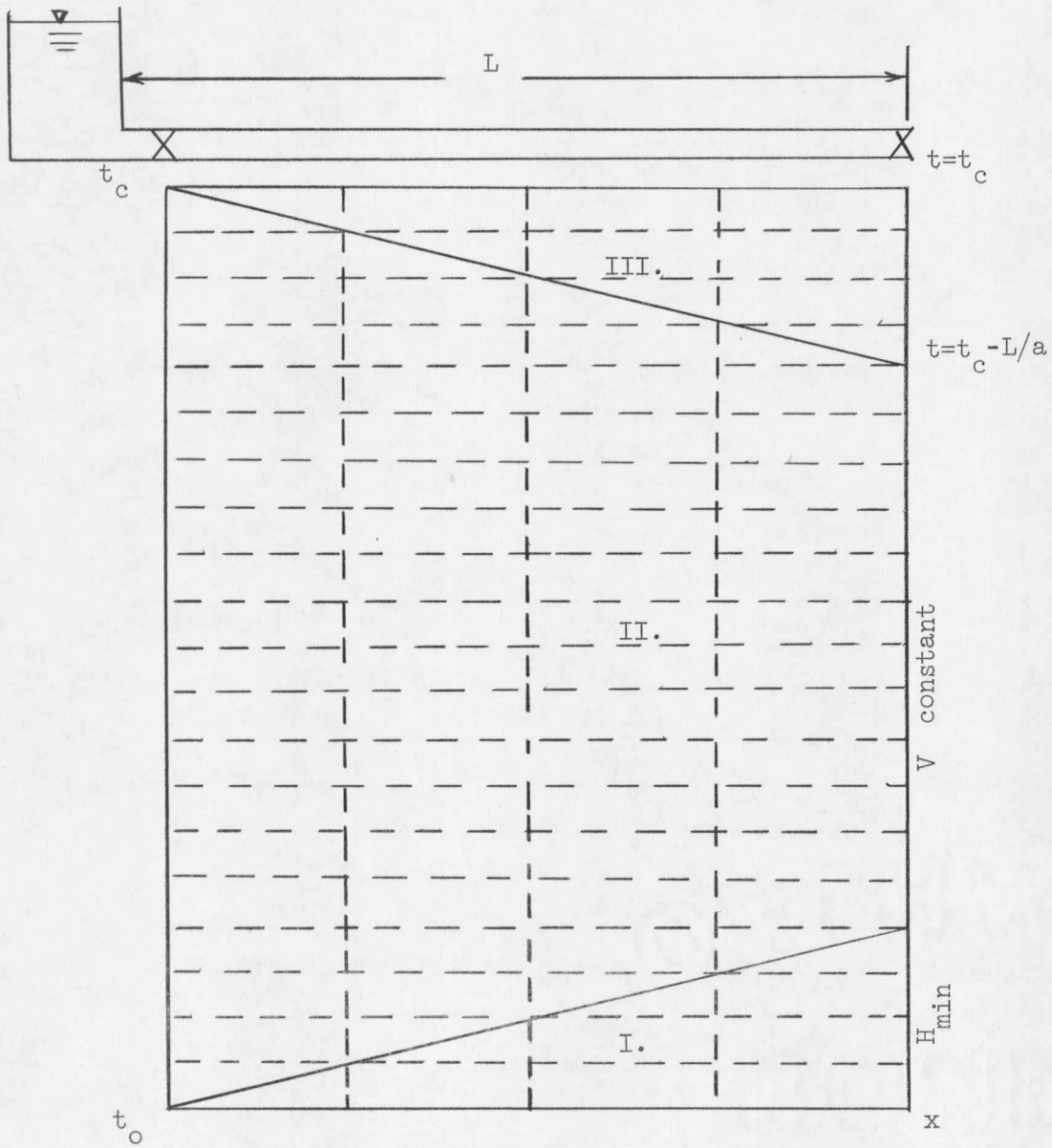


Figure 6. Design of valve closure rates in a two valve pipeline

velocities are determined at all points within these regions by use of the energy equation. Region II is a transient region induced by increasing the heads in the pipe.

Because the heads and velocities are known at the downstream valve at all times in regions I and II and because velocities are known at the downstream valve in region II, the method of design requiring the fewest assumptions is to specify the rate of head increase during region II at the downstream valve. The heads and velocities at the interior points and at the points immediately downstream of the upstream valve can be found by application of the same method used in design case II. If the heads and velocities are known immediately upstream and downstream from the pipe in question, Eq. (24) may be used to solve for the valve movements that will yield the arbitrary rate of head increase that was specified.

E. Design Procedure

Now that the basic design methods have been presented, all the tools required to determine the method for operating all of the valves are available. A detailed description of the application of these tools to the injection system will now be described.

Valve 2 was selected as the key valve to be stroked in the first phase of the valving operation. As valve 2 closes and reduces the flow into pipe A, there are several conditions imposed on the system. First, the low pressure pump must not experience any transient impulses. If

this is to be true, the flow in pipe 1 (see Figure 5) must be steady. This in turn requires that a constant head at junction 1 be maintained. Valve 1 must be operated to hold the pressure constant at junction 1 as valve 2 closes. Because junction 1 is, in effect, a constant head reservoir, the procedure introduced as design case I may be applied to pipe 3.

The difference between the flow rate in pipe 1 and that in pipe 3 is the flow rate in pipe 2. Thus, the flow rate in pipe 2 is known at all times after design case I is applied to pipe 3. Because the flow rate and head is known at all times at the upstream end of pipe 2, design case II can be applied to pipe 2 to determine the heads and velocities at the upstream side of valve 1.

Pipe 4 recirculates the flow from pipe 2 back to the wood chip mixing tank that feeds the low pressure pump. This tank creates a constant head reservoir at the downstream end of pipe 4. The flow velocities entering pipe 4 from pipe 2 can be found at any time by continuity. Design case III applied to pipe 4 will give the heads at the pipe 4 side of valve 1.

Because no flow fluctuations are to occur in pipe 7 as valve 2 closes, water is added to the injection line through valve 4, into pipe 6, at such a rate that the flow rate is held constant in pipe 7. Because the flow is constant in pipe 7, the pressure head at junction 2 must be constant, and the junction is, in effect, a constant head reservoir for pipes 5 and 6. The flow rate into pipe 5 can be determined, by continuity, from pipe 3 for all times. Design case III can be applied

to pipe 5 to determine the heads at the pipe 5 side of valve 2 and to determine the flow rate entering junction 2 at any instant. The flow rate entering junction 2 from pipe 6 at any time must equal the difference between the flow rate in pipe 7 and pipe 5. Thus, the velocity and head is known for all times at the reservoir end of pipe 6. Design case II can be applied to pipe 6 to find the heads and velocities at valve 4.

At the end of phase I of the valving operation, all flow through pipes 3 and 5 is stopped and the wood chip flow is merely recirculating through pipes 1, 2, and 4. The accumulator at this instant is supplying the total flow rate to the injection line. The switching process now enters phase 2 in which valve 6 starts to close and valve 4 starts to open in order to increase the pressure in injection line A which is a combination of pipes 6 and 7. This then becomes the case analyzed in design case IV.

Pipe 9 is a special case of a pipe with a valve at one end and a reservoir at the other, because it empties into a tank which feeds the high pressure pump. However, because it is required that the flow from valve 6 be constant, there will be no transients induced in pipe 9. The energy equation is applied to find the heads and velocities at any point in the pipe for any time.

Pipe 8 is considered to be of such short length that all transients are instantaneously received at the accumulator, and hence, the pressure head upstream of valve 4 is equal to the accumulator head at all times.

The flow rate in pipe 8 is found by continuity from the flow demands of pipe 6.

A review of the preceding discussion will show that at this moment the heads and velocities are known on both sides of all the valves during the first two phases of the switching process. By using Eq. (24) the tau values for valves 1, 2, 4, and 6 can be calculated for all time increments during the first two phases.

At this point in time high pressures exist in lines A and B, and phase 3 is initiated. Valve 5 starts to switch the flow to the main pipeline, and valve 3 starts to switch the flow from the high pressure pump to line A. Valves 3 and 5 have the same rate of movement.

The rate at which valves 3 and 5 operate depends on transients created in lines 5 and 12. As valve 3 starts to add flow to line 5 from the high pressure pump, it will start to decrease the flow rate in line 12. Transients will be generated in these pipes as the flow in line 5 is accelerated and that in line 12 is decelerated. Valve 4 must start to decrease the flow from the accumulator through line 6 into line 7 at a rate that will keep the flow rate in line 7 constant. Likewise, valve 7 must add flow from the accumulator through line 11 to line 10 at a rate that will keep the flow in line 10 constant.

In this analysis the switching valves will be assumed to divert flow to each pipe in a proportion to the flow area that is open to each pipe at any instant of time. This is a valid assumption if there is negligible head loss across the valve and if the head on both sides of

the switching valve is the same.

As the flow in pipes 7 and 10 must be steady at all times, junctions 2 and 3 must act as constant head reservoirs for pipes 5, 6, 11, and 12. When valve 3 is given an arbitrary movement, the flows into pipes 5 and 12 are proportional to the flow area open to each pipe, permitting design case III to be applied to pipes 5 and 12. Design case III determines the flow in pipe 5 at junction 2 and the flow in pipe 12 at junction 3 at any instant. The flow in pipe 6 at junction 2 is the difference in the constant flow rate in pipe 7 and the flow rate in pipe 5 at any instant. Likewise, the flow in pipe 11 at any instant is the difference in the flow rate in pipe 12 at any instant and the constant flow rate in pipe 10. This allows design case II to be used for pipes 6 and 11, and the heads and velocities at the downstream side of valves 4 and 7 can be determined. Because the head upstream of these valves is known for all times, the tau values for these valves can be calculated with Eqs. (24).

In phase IV valve 7 will have the same method of operation that valve 4 had in phase II, except it will be in reverse. Likewise, valve 6 will reverse the method of operation of phase II in phase IV. Valves 1, 2, and 4 will reverse their method of operation in phase I in phase V.

CHAPTER V

PHYSICAL DIMENSIONS OF THE INJECTION SYSTEM

Before the analysis described in the preceding chapter can be applied to the injection system, physical dimensions must be assigned to the pipes, and the initial flow conditions in the system must be established such that heads and velocities are initially known at all the valves and junctions.

The length, diameter, friction factor and boundaries at the end of each pipe are shown in Table I. The following abbreviations are used in the boundary column of the table: L.P.--low pressure, Jct.--junction, W.C.--wood chip, and H.P.--high pressure. In the case of pipes 5, 7, 10, and 11 there are two valves given for a single boundary, because during phase II valves 2 and 6 are used as the boundaries of these pipes and during phase III valves 3 and 5 are used as the boundaries of these pipes. In order to make these conditions amenable, valve 3 is located within one foot of valve 2, and valve 5 is located within one foot of valve 6.

The initial flow velocity is 8 feet per second in pipes 1, 3, 5, 7, 9, 10, and 12. Initially, there is no flow in the other pipes. The head at the low pressure pump is 131.126 feet of water and the head at the high pressure pump is 1669.518 feet of water. By applying the basic energy equation of fluid mechanics to the system and by assuming a head loss across each valve, the head at any point in the system is determined. The head at junction 1 is 130.008 feet; the head at junction 2 is 137.557 feet; and the head at junction 3 is 1667.081 feet. The water level in

TABLE I

PHYSICAL DIMENSIONS OF THE INJECTION SYSTEM

Pipe No. (1)	Length (feet) (2)	Diameter (inches) (3)	Friction Factor (4)	Boundary (5)
1	25	8.0	0.03	L.P. Pump Jct. 1
2	25	8.0	0.03	Jct. 1 Valve 1
3	25	8.0	0.03	Jct. 1 Valve 2
4	25	8.0	0.03	Valve 1 W.C. Mix Tank
5	25	8.0	0.03	Valve 2 or 3 Jct. 2 or 3
6	25	8.0	0.03	Jct. 2 Valve 4
7	1500	8.0	0.03	Jct. 2 Valve 5 or 6
8	1	8.0	0.03	Valve 4 Accumulator
9	1342	8.0	0.03	Valve 6 H.P. Feed Tank
10	1500	8.0	0.03	Valve 5 or 6 Jct. 3
11	25	8.0	0.03	Jct. 3 Valve 7
12	25	8.0	0.03	Jct. 3 Valve 2 or 3
13	1	8.0	0.03	Valve 7 Accumulator

the wood chip mix tank is assumed to be level with the top of pipe 4. Likewise, a similar assumption is made for pipe 9 as it enters the feed tank to the high pressure pump providing a constant zero head at that end of pipe 9.

Table II shows the heads and velocities at the upstream and downstream side of each valve for the initial operating condition in columns 2 and 3. The heads and velocities upstream and downstream of each valve, when the valve is completely open is shown in columns 4 and 5. These latter values of heads and velocities are used to calculate H_o and V_o for use in Eq. (24) which is used to calculate the value of tau (the ratio of the product of the orifice coefficient and gate area of the valve at any time to the product of the orifice coefficient and gate area when the valve is completely open). The heads in the table have units of feet of water and the velocities are given in feet per second. There are no listings in columns 4 and 5 for valves 3 and 5 because tau values are not assigned to these switching valves.

TABLE II

VALVE FLOW CONDITIONS

Boundary (1)		Initial Conditions		Fully Open Valve Conditions	
		Upstream (2)	Downstream (3)	Upstream (4)	Downstream (5)
Valve 1	H	130.008*	0.000	65.000	64.700
	V	0.000**	0.000	61.100	61.100
Valve 2	H	128.890	128.675	128.890	128.675
	V	8.000	8.000	8.000	8.000
Valve 3	H	1668.400	1668.199		
	V	8.000	8.000		
Valve 4	H	1668.499	127.557	1668.499	1668.199
	V	0.000	0.000	8.000	8.000
Valve 5	H	1600.000	1599.700		
	V	8.000	8.000		
Valve 6	H	60.241	60.000	60.241	60.000
	V	8.000	8.000	8.000	8.000
Valve 7	H	1668.499	1667.081	1668.499	1668.199
	V	0.000	0.000	8.000	8.000

* heads in feet of water

** velocities in feet per second

CHAPTER VI

RESULTS

The results of the analysis described in Chapter 4 are given in this chapter. Because the effect of wood chips on wave velocities is not known, a complete analysis of the injection system was made for wave velocities of 2000, 2500, and 3000 feet per second. The results illustrated in this chapter, for a wave velocity of 2500 feet per second, are typical of those obtained for the other wave speeds. The operating rates of valves 1, 2, 4, and 6 for all wave speeds are listed in tables I-A, I-B, I-C, II-A, II-B, II-C, III-A, III-B, III-C, IV-A, IV-B, and IV-C in the appendix. Valve 3 is not included in the tables because its rate of movement is the same for all wave speeds and is defined in terms of percent of valve area open to pipe 5 at any instant, rather than in terms of tau. The rate of movement of valve 3 is defined in Figure 9. The operating rate of valve 7 is also excluded from the appendix. As explained previously, valve 7 is operated in exact reverse in phases III, IV, and V of the valving operation of the rate of movement of valve 4 in phases I, II, and III.

The time rate of movement of the valves is defined in terms of a tau value at any instant of time. The operating rates of valves 1, 2, 4, 6, and 7 in terms of tau are plotted versus time in Figures 7, 8, 9, 10, and 11.

The sequence of the valve operations is shown in Figure 12. At the bottom of each of the vertical bars are the letters o and c or A and B. If the lines in the vertical bars slant from o to c, the valve is moving

from an open position to a closed position. If they slant in the opposite direction the valve is opening. The lines merely represent the time during which the valve is operating. In the case of switching valves 3 and 5, the lines slope from B to A to represent the switching of the high pressure injection flow into the main pipeline from line "B" (pipe 10) to line "A" (pipe 7). The horizontal dashed lines in Figure 12 represent the boundaries dividing the five phases of the valving operation. The times shown in Figure 12 are listed in Table III.

The effect that wave speed has on the total operation time is illustrated in Figure 13. This figure shows that the total time required to complete the switching operation increases exponentially as the wave speed is decreased.

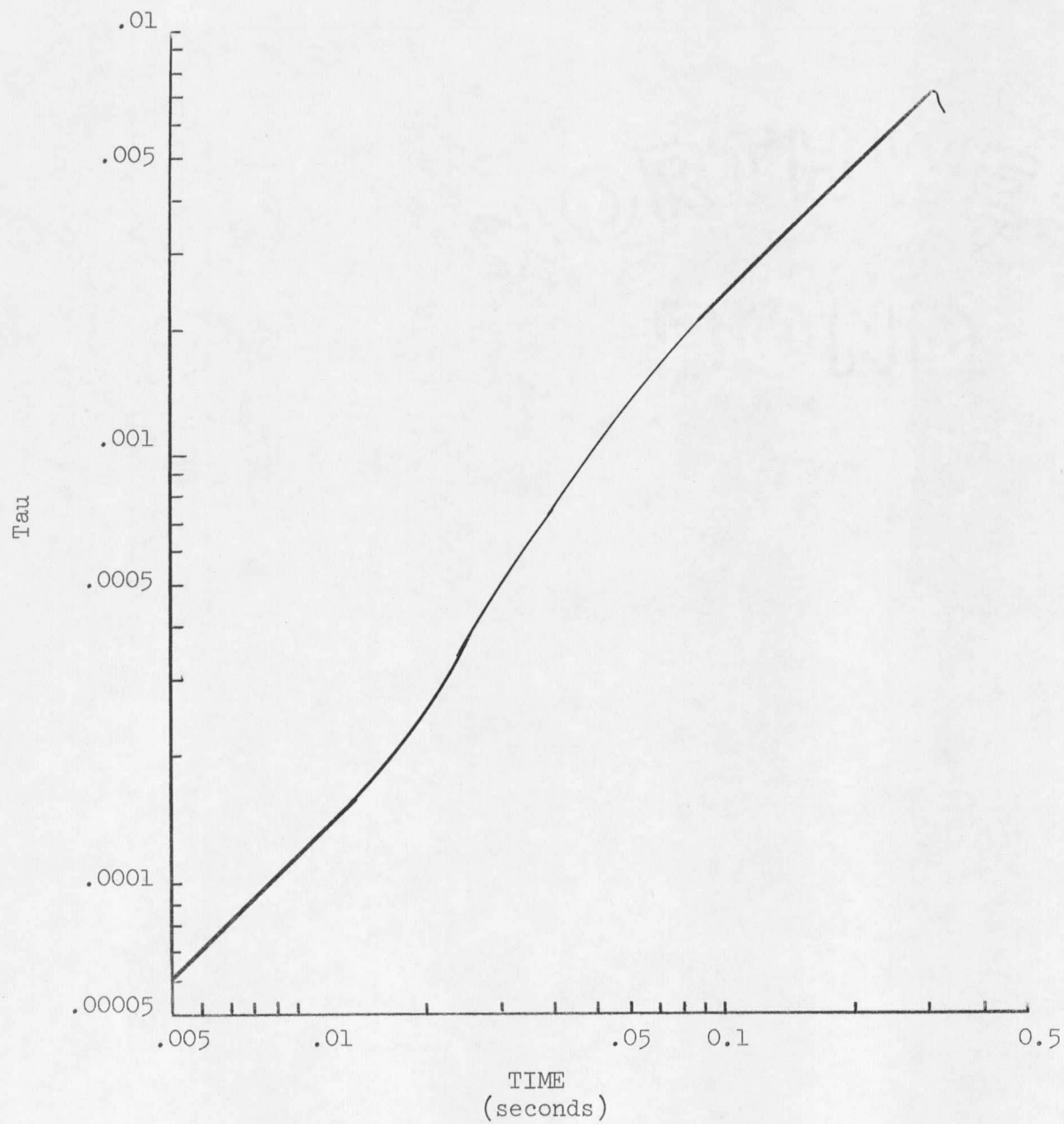


Figure 7. Operating rate of valve 1
for A = 2500 fps

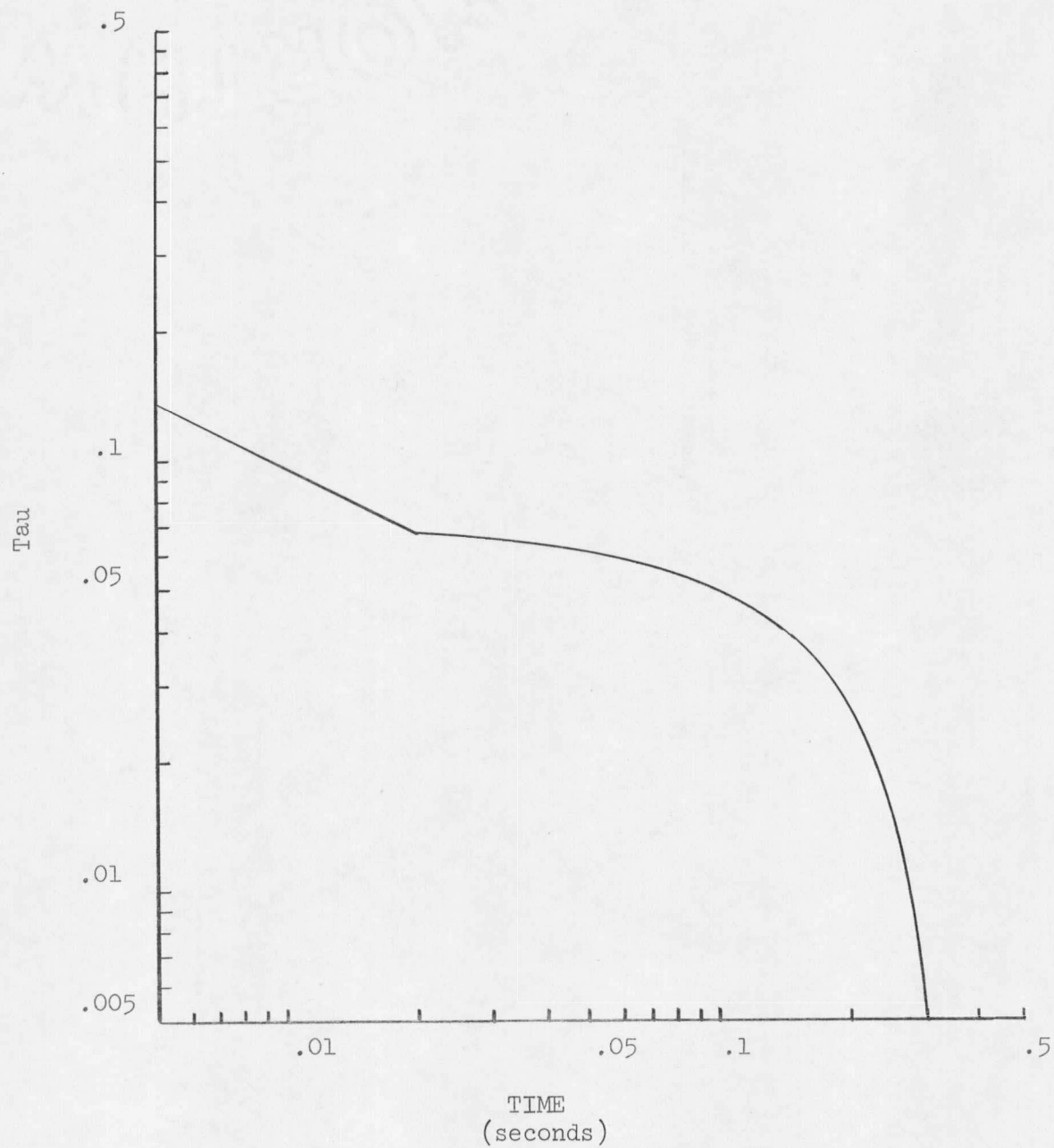


Figure 8. Operating rate of valve 2
for $A = 2500$ fps

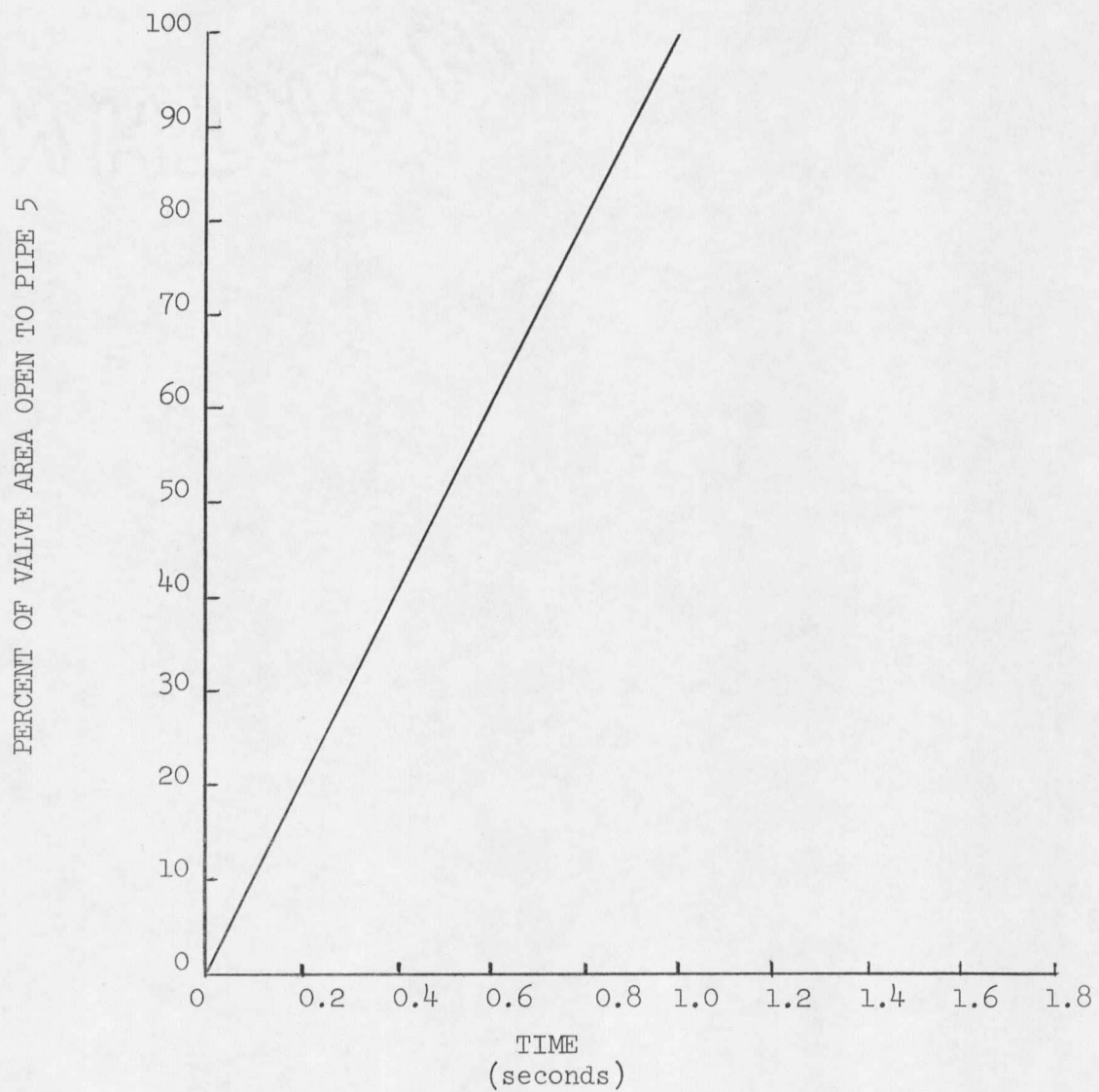


Figure 9. Operating rate of valve 3
for $A = 2500$ fps

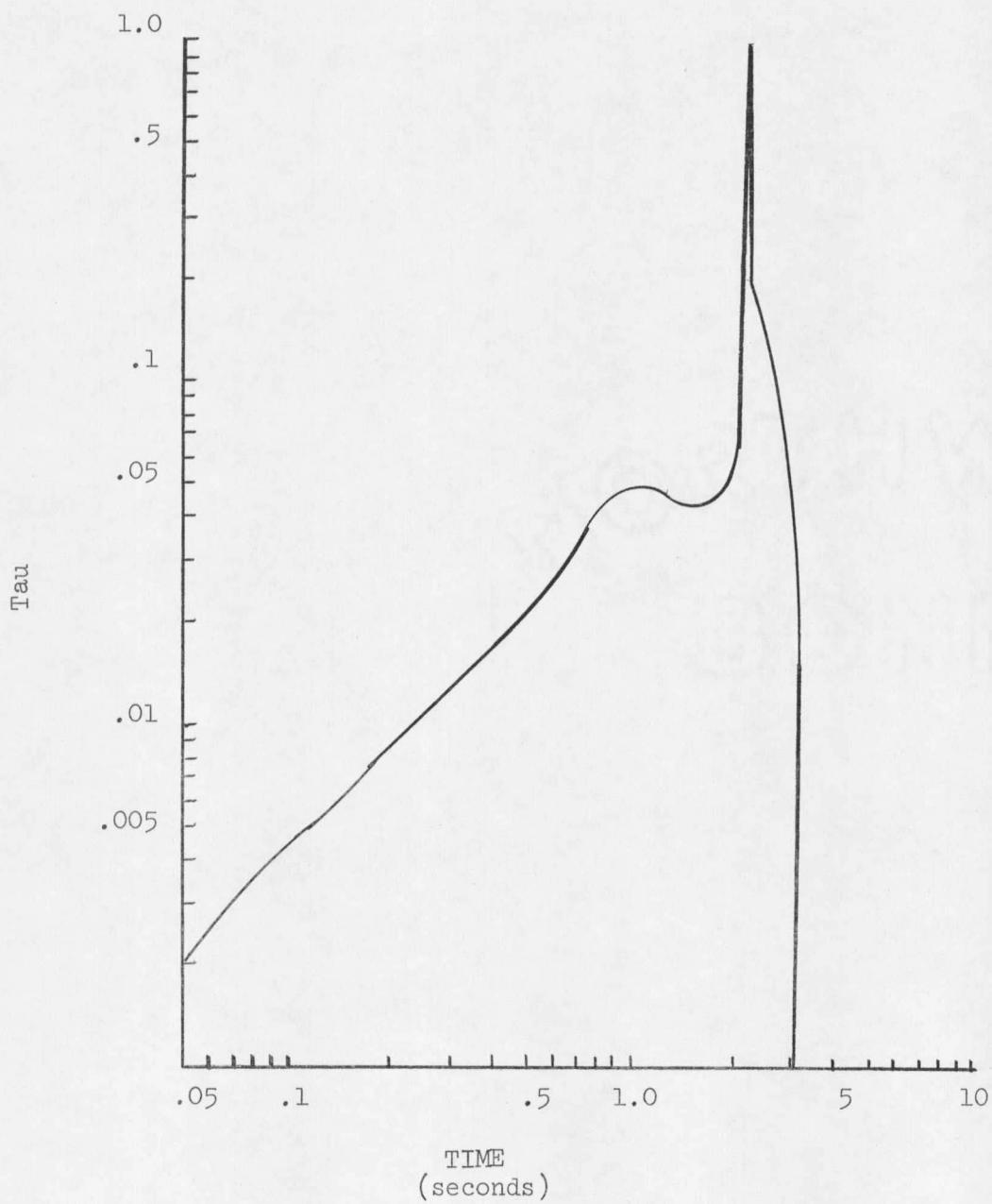


Figure 10. Operating rate of valve 4
for $A = 2500$ fps

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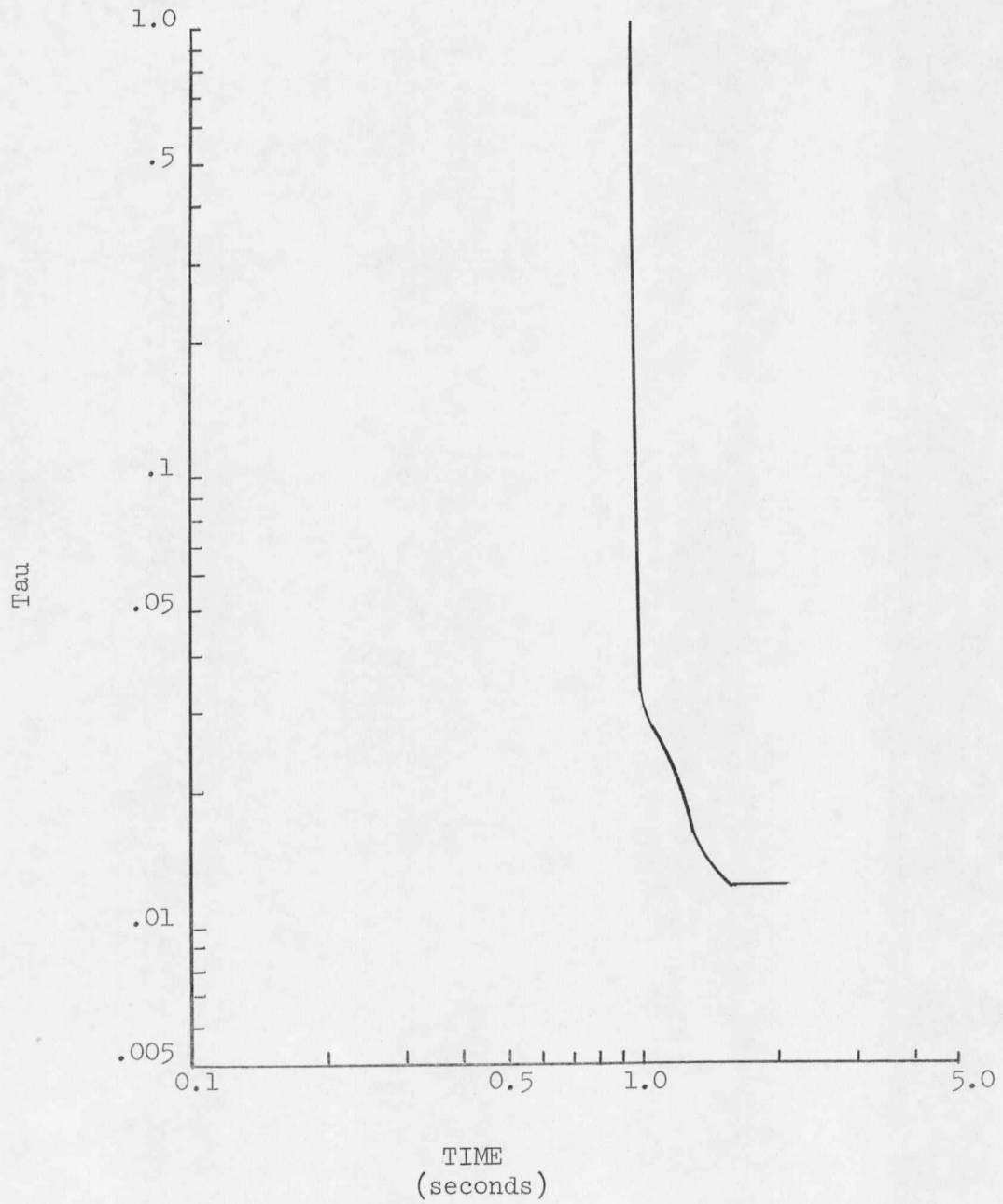


Figure 11. Operating rate of valve 6
for $A = 2500$ fps

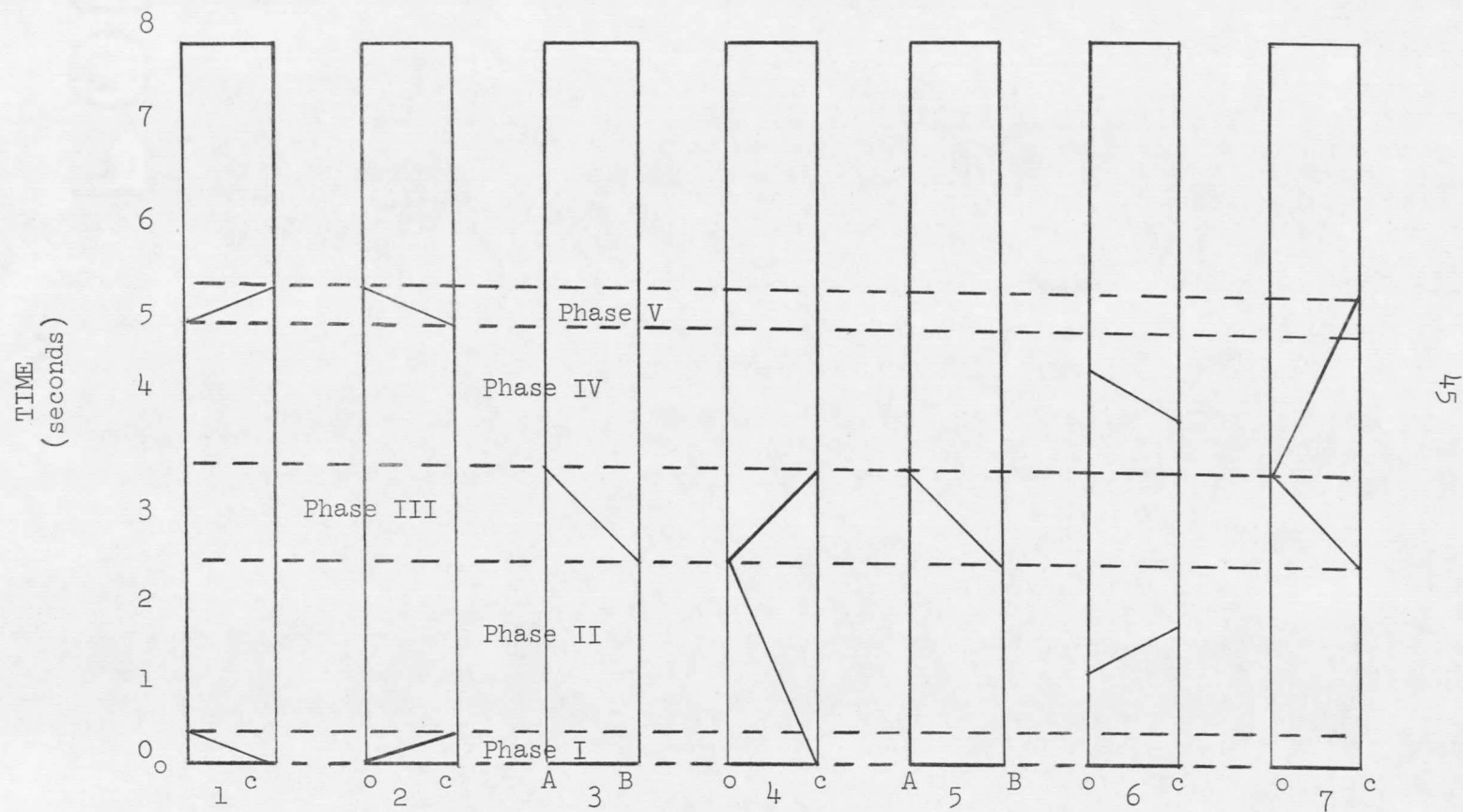


Figure 12. Sequence of valve operations for A = 2500 fps

TABLE III

SEQUENCE AND TIMING OF VALVE OPERATIONS

A = 2500 fps

Valve		Phase I	Phase II	Phase III	Phase IV	Phase V
1	TB	0.00000*				4.98753
	TF	0.32500**				5.32253
2	TB	0.00000				4.98755
	TF	0.32500				5.32253
3	TB			2.15500		
	TF			3.16753		
4	TB	0.00000	0.32500	2.15500		
	TF	0.32500	2.1550	3.16753		
5	TB			2.15500		
	TF			3.16753		
6	TB		0.93500		3.44253	
	TF		1.54500		4.05253	
7	TB			2.15500	3.16753	4.98753
	TF			3.16753	4.98753	5.32253

*Time beginning movement in seconds

**Time ending movement in seconds

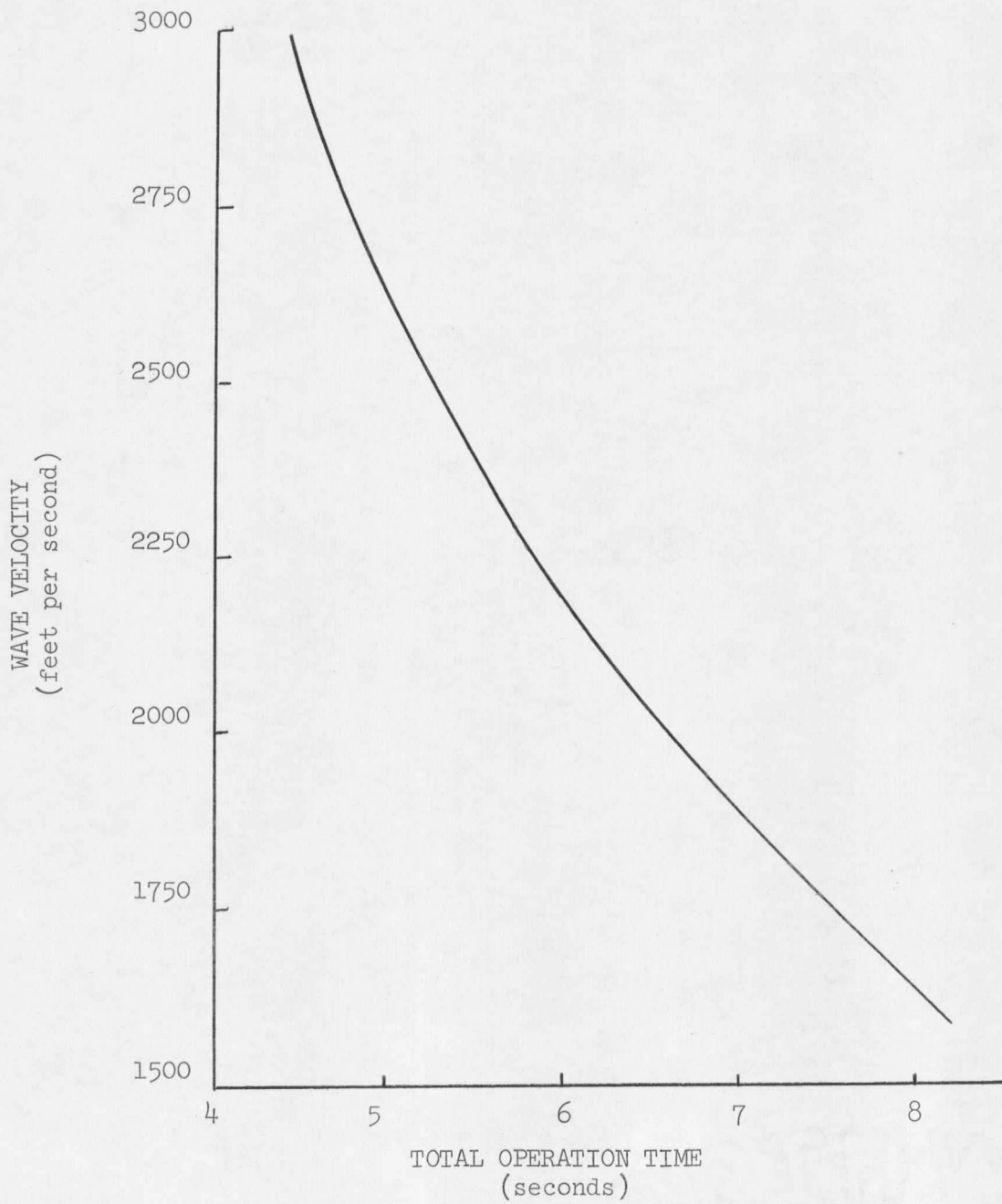


Figure 13. Wave velocity as a function of time

CHAPTER VII

DISCUSSION AND CONCLUSIONS

The method of solution and the results of the analysis illustrate three important points that require discussion: (1) the assumption that flow through the switching valves is proportional to the flow area open to each pipe, (2) the calculated values of τ appear quite small, and (3) the majority of the total switching time of the system is taken by phases II and IV of the valving operation. These phases involve the selection of an arbitrary number of time steps.

A. Flow Through Switching Valves

First, the assumption that flow entering a switching valve is divided among the outlet pipes in proportion to the area open to each pipe at any instant is a valid only if the heads on all sides of the switching valve are nearly equal, because there is no extreme pressure difference forcing a greater amount of flow through one opening rather than another. The condition of nearly equal heads is met at valve 5, but valve 3 is an exception due to transients generated as it shifts the flow from one pipe to the other. The transients are generated at valve 3 because the flow in pipe 5 is initially at rest and must be accelerated to 8 feet per second as valve 3 opens the flow from the high pressure pump to line 5. Likewise, the flow in pipe 12 must be decelerated from 8 feet per second to zero during this operation. The acceleration and deceleration of the fluid requires pressure increases and decreases on the downstream sides

of valve 3. The net effect is to force more flow than is predicted into pipe 12.

In this analysis, the velocity at valve 3 in pipe 5 was arbitrarily increased by 0.02 feet per second each time increment for 400 time increments, thus making the transients generated by this valve movement quite small due to the long operation rate. Application of design case III to pipe 5 indicated that the maximum increase in head at valve 3, above the steady state value, was 9.938 feet. When this head increase is compared with the steady state head of 1668.199 feet it is negligible. The transients can be eliminated completely by locating junctions 2 and 3 as close as possible to valve 3, thus eliminating the need to accelerate and decelerate the water in pipes 5 and 12.

B. Small Values of Tau

The second item of discussion is the unusually small values of tau that were calculated for each valve. A review of Eq. (24), rewritten below in slightly different form, demonstrates why the values of tau are quite small.

$$\tau = \frac{\frac{V}{V_o}}{\frac{H - HD}{H_o - HD_o}} \quad (29)$$

H is the head immediately upstream of the valve and HD is the head immediately downstream of the valve. The quantity $(H_o - HD_o)$ is the head loss across the valve when it is wide open. The value of this quantity is the

key factor in explaining the small values of τ . In this analysis, this head loss value was assumed to be between 0.2 and 0.3 feet for all the valves. These values were arbitrarily assumed and are typical of a ball type valve. These small values of head loss make the denominator of Eq. (29) large for an instantaneous head drop across the valve of just a few feet. Because the numerator of Eq. (29) is ordinarily less than or equal to one (during the pressure increasing phases the ratio V/V_0 becomes greater than one), the value of τ becomes quite small quite rapidly. The selection of a type of valve which has higher steady state head loss characteristics would increase the magnitude of τ . This fact should be recognized in selecting a valve type for use in the injection system.

C. Major Time Phases of Operation

The third item to be discussed is the time requirements of phases II and IV. These phases require an increase in pressure in line "A" (pipe 7) and a decrease in pressure in "B" (pipe 10). They are applications of design case IV in which the head is increased at valve 6 over an arbitrary number of time increments. In this analysis, the incremental length of pipe, dx , in "A" and "B" during the pressure increasing period was 152.5 feet compared with a dx of 6.25 feet in the other phases. This means that the time increments in phases II and IV are 24.4 times larger than the other phases. The number of time steps over which the head is increased is thus quite critical in determining the total operation time required by the valves. In this analysis 10 time steps were taken

to increase the head. With this number of time steps the combined times of phases II and IV represent 66.2%, 67.8%, and 69.9% of the total switching time for the respective wave velocities of 3000, 2500, and 2000 feet per second.

Obviously, phases II and IV should be made as short as possible by reducing the number of time increments of pressure increase. The rate at which pressure may be increased, however, is limited by the accumulator. As the pressure in the pipe increases, the water in the pipe compresses and the pipe expands axially and radially. The volume change requires the accumulator to supply an additional amount of flow to fill the expanding pipe. The faster the pressure increase, the faster the flow must be from the accumulator in order to adjust to the volume increases. If the flow demands from the accumulator become too large, although they occur over a short period of time, the mechanism used in the accumulator to maintain constant pressure in the tank may not be able to meet the flow requirements. Pressure in the accumulator will then decrease, invalidating the assumption that the accumulator produces a constant head. Thus, the rate of pressure increase is controlled by the physical limitations of the accumulator.

D. Conclusions

The method of analysis and design described in this paper provides a method for designing the operation of the individual valves in the proposed injection system so that a transient-free flow is maintained in the

main pipeline.

Once physical dimensions are assigned to the injection system this method of analysis may be used to determine the time rate of operation of the individual valves in terms of tau (τ) as a function of time. Valves will then have to be built which will physically reproduce these tau values in an actual operation.

One of the most important factors determining the operating rates of the valves is the value of the wave speed. As illustrated in Figure 13, the time required for the valving operation increases rapidly as the wave speed decreases. A small amount of entrained air can cause a tremendous decrease in the wave speed. One percent air entrainment can reduce the wave speed by nearly 90 percent. The author therefore recommends that extensive testing be made on the effect that wood chips will have on the wave speed as they will more than likely entrain large amounts of air as they are mixed with water.

In addition to extensive testing on the effects of wood chip entrainment on wave speeds, the author also recommends that the lengths of pipes 5 and 12 be shortened or that they be eliminated in order to reduce the transients generated in these pipes in phase III of the injection operation.

APPENDIX

TABLE I-A

OPERATION

OF

VALVE NO. 1

A= 2000 FPS

TAU	TIME
0.00000	0.00000
0.00003	0.00312
0.00007	0.00624
0.00011	0.00936
0.00015	0.01248
0.00019	0.01560
0.00023	0.01872
0.00028	0.02184
0.00032	0.02496
0.00040	0.02808
0.00049	0.03120
0.00057	0.03432
0.00065	0.03744
0.00073	0.04056
0.00081	0.04368
0.00089	0.04680
0.00097	0.04992
0.00105	0.05304
0.00113	0.05616
0.00121	0.05928
0.00129	0.06240
0.00136	0.06552
0.00144	0.06864
0.00152	0.07176
0.00160	0.07488
0.00168	0.07800
0.00176	0.08112
0.00184	0.08424
0.00192	0.08736
0.00200	0.09048
0.00208	0.09360
0.00215	0.09672
0.00223	0.09984
0.00231	0.10296
0.00239	0.10608
0.00247	0.10920
0.00255	0.11232

0.00262	0.11544
0.00270	0.11856
0.00278	0.12168
0.00286	0.12480
0.00293	0.12792
0.00301	0.13104
0.00309	0.13416
0.00317	0.13728
0.00325	0.14040
0.00333	0.14352
0.00340	0.14664
0.00348	0.14976
0.00356	0.15288
0.00363	0.15600
0.00371	0.15912
0.00379	0.16224
0.00386	0.16536
0.00394	0.16848
0.00402	0.17160
0.00410	0.17472
0.00417	0.17784
0.00425	0.18096
0.00433	0.18408
0.00440	0.18720
0.00448	0.19032
0.00456	0.19344
0.00464	0.19656
0.00471	0.19968
0.00479	0.20280
0.00486	0.20592
0.00494	0.20904
0.00503	0.21216
0.00510	0.21528
0.00517	0.21840
0.00525	0.22152
0.00533	0.22464
0.00541	0.22776
0.00549	0.23088
0.00557	0.23400
0.00564	0.23712
0.00572	0.24024
0.00580	0.24336
0.00587	0.24648
0.00594	0.24960
0.00603	0.25272
0.00609	0.25584
0.00617	0.25896
0.00626	0.26208
0.00633	0.26520

0.00640	0.26832
0.00648	0.27144
0.00657	0.27456
0.00664	0.27768
0.00673	0.28080
0.00680	0.28392
0.00687	0.28704
0.00696	0.29016
0.00703	0.29328
0.00711	0.29640
0.00718	0.29952
0.00726	0.30264
0.00723	0.30576
0.00708	0.30888
0.00694	0.31200
0.00681	0.31512
0.00669	0.31824
0.00658	0.32136
0.00648	0.32448
0.00638	0.32760
0.00633	0.33072

TABLE I-B

OPERATION

OF

VALVE NO. 1

A= 2500 FPS

TAU	TIME
0.00000	0.00000
0.00003	0.00250
0.00006	0.00500
0.00009	0.00750
0.00012	0.01000
0.00015	0.01250
0.00018	0.01500
0.00022	0.01750
0.00026	0.02000
0.00032	0.02250
0.00039	0.02500
0.00045	0.02750
0.00052	0.03000
0.00058	0.03250
0.00065	0.03500
0.00071	0.03750
0.00078	0.04000
0.00084	0.04250
0.00090	0.04500
0.00097	0.04750
0.00103	0.05000
0.00109	0.05250
0.00116	0.05500
0.00122	0.05750
0.00136	0.06000
0.00142	0.06250
0.00149	0.06500
0.00155	0.06750
0.00162	0.07000
0.00168	0.07250
0.00175	0.07500
0.00181	0.07750
0.00185	0.08000
0.00192	0.08250
0.00198	0.08500
0.00205	0.08750
0.00211	0.09000

0.00217	0.09250
0.00223	0.09500
0.00230	0.09750
0.00236	0.10000
0.00242	0.10250
0.00248	0.10500
0.00254	0.10750
0.00261	0.11000
0.00267	0.11250
0.00273	0.11500
0.00280	0.11750
0.00286	0.12000
0.00292	0.12250
0.00298	0.12500
0.00305	0.12750
0.00311	0.13000
0.00317	0.13250
0.00323	0.13500
0.00329	0.13750
0.00336	0.14000
0.00342	0.14250
0.00348	0.14500
0.00354	0.14750
0.00360	0.15000
0.00366	0.15250
0.00373	0.15500
0.00379	0.15750
0.00385	0.16000
0.00391	0.16250
0.00397	0.16500
0.00404	0.16750
0.00410	0.17000
0.00416	0.17250
0.00422	0.17500
0.00428	0.17750
0.00434	0.18000
0.00441	0.18250
0.00447	0.18500
0.00452	0.18750
0.00459	0.19000
0.00465	0.19250
0.00471	0.19500
0.00477	0.19750
0.00484	0.20000
0.00490	0.20250
0.00495	0.20500
0.00503	0.20750
0.00508	0.21000
0.00515	0.21250

0.00520	0.21500
0.00527	0.21750
0.00533	0.22000
0.00539	0.22250
0.00546	0.22500
0.00533	0.22750
0.00539	0.23000
0.00545	0.23250
0.00552	0.23500
0.00557	0.23750
0.00564	0.24000
0.00569	0.24250
0.00575	0.24500
0.00595	0.24750
0.00601	0.25000
0.00607	0.25250
0.00613	0.25500
0.00619	0.25750
0.00625	0.26000
0.00632	0.26250
0.00638	0.26500
0.00643	0.26750
0.00650	0.27000
0.00656	0.27250
0.00663	0.27500
0.00669	0.27750
0.00675	0.28000
0.00681	0.28250
0.00686	0.28500
0.00694	0.28750
0.00700	0.29000
0.00706	0.29250
0.00711	0.29500
0.00718	0.29750
0.00724	0.30000
0.00731	0.30250
0.00738	0.30500
0.00719	0.30750
0.00704	0.31000
0.00690	0.31250
0.00677	0.31500
0.00664	0.31750
0.00653	0.32000
0.00642	0.32250
0.00632	0.32500

TABLE I-C

OPERATION

OF

VALVE NO. 1

A= 3000 FPS

TAU	TIME
0.00000	0.00000
0.00002	0.00208
0.00005	0.00416
0.00007	0.00624
0.00010	0.00832
0.00013	0.01040
0.00015	0.01248
0.00018	0.01456
0.00022	0.01664
0.00027	0.01872
0.00032	0.02080
0.00038	0.02288
0.00043	0.02496
0.00048	0.02704
0.00054	0.02912
0.00059	0.03120
0.00065	0.03328
0.00070	0.03536
0.00075	0.03744
0.00081	0.03952
0.00086	0.04160
0.00091	0.04368
0.00097	0.04576
0.00102	0.04784
0.00107	0.04992
0.00113	0.05200
0.00118	0.05408
0.00123	0.05616
0.00129	0.05824
0.00134	0.06032
0.00139	0.06240
0.00145	0.06448
0.00150	0.06656
0.00155	0.06864
0.00160	0.07072
0.00165	0.07280
0.00171	0.07488

0.00176	0.07696
0.00181	0.07904
0.00186	0.08112
0.00192	0.08320
0.00197	0.08528
0.00202	0.08736
0.00208	0.08944
0.00213	0.09152
0.00218	0.09360
0.00223	0.09568
0.00229	0.09776
0.00234	0.09984
0.00239	0.10192
0.00244	0.10400
0.00249	0.10608
0.00254	0.10816
0.00260	0.11024
0.00265	0.11232
0.00270	0.11440
0.00275	0.11648
0.00280	0.11856
0.00285	0.12064
0.00291	0.12272
0.00296	0.12480
0.00301	0.12688
0.00306	0.12896
0.00312	0.13104
0.00317	0.13312
0.00322	0.13520
0.00327	0.13728
0.00332	0.13936
0.00338	0.14144
0.00343	0.14352
0.00348	0.14560
0.00353	0.14768
0.00358	0.14976
0.00363	0.15184
0.00368	0.15392
0.00374	0.15600
0.00379	0.15808
0.00383	0.16016
0.00389	0.16224
0.00395	0.16432
0.00400	0.16640
0.00405	0.16848
0.00410	0.17056
0.00415	0.17264
0.00420	0.17472
0.00426	0.17680

0.00672	0.27664
0.00676	0.27872
0.00430	0.17888
0.00435	0.18096
0.00440	0.18304
0.00445	0.18512
0.00451	0.18720
0.00456	0.18928
0.00462	0.19136
0.00466	0.19344
0.00472	0.19552
0.00477	0.19760
0.00482	0.19968
0.00487	0.20176
0.00492	0.20384
0.00497	0.20592
0.00502	0.20800
0.00508	0.21008
0.00512	0.21216
0.00517	0.21424
0.00522	0.21632
0.00527	0.21840
0.00532	0.22048
0.00539	0.22256
0.00544	0.22464
0.00548	0.22672
0.00554	0.22880
0.00559	0.23088
0.00564	0.23296
0.00569	0.23504
0.00575	0.23712
0.00579	0.23920
0.00583	0.24128
0.00590	0.24336
0.00594	0.24544
0.00599	0.24752
0.00604	0.24960
0.00609	0.25168
0.00614	0.25376
0.00621	0.25584
0.00626	0.25792
0.00630	0.26000
0.00637	0.26208
0.00641	0.26416
0.00647	0.26624
0.00652	0.26832
0.00657	0.27040
0.00661	0.27248
0.00666	0.27456

0.00682	0.28080
0.00687	0.28288
0.00692	0.28496
0.00697	0.28704
0.00703	0.28912
0.00709	0.29120
0.00713	0.29328
0.00719	0.29536
0.00723	0.29744
0.00729	0.29952
0.00734	0.30160
0.00740	0.30368
0.00730	0.30576
0.00712	0.30784
0.00698	0.30992
0.00683	0.31200
0.00671	0.31408
0.00658	0.31616
0.00647	0.31824
0.00636	0.32032
0.00632	0.32240

TABLE II-A

OPERATION

OF

VALVE NO. 2

A= 2000 FPS

TAU	TIME
1.00000	0.00000
0.10998	0.00312
0.09458	0.00624
0.08490	0.00936
0.07747	0.01248
0.07166	0.01560
0.06690	0.01872
0.06620	0.02184
0.06589	0.02496
0.06561	0.02808
0.06530	0.03120
0.06454	0.03432
0.06383	0.03744
0.06307	0.04056
0.06231	0.04368
0.06160	0.04680
0.06045	0.04992
0.05931	0.05304
0.05819	0.05616
0.05750	0.05928
0.05676	0.06240
0.05608	0.06552
0.05534	0.06864
0.05458	0.07176
0.05424	0.07488
0.05390	0.07800
0.05355	0.08112
0.05277	0.08424
0.05206	0.08736
0.05127	0.09048
0.05056	0.09360
0.04989	0.09672
0.04878	0.09984
0.04769	0.10296
0.04666	0.10608
0.04596	0.10920
0.04524	0.11232

0.04459	0.11544
0.04383	0.11856
0.04305	0.12168
0.04267	0.12480
0.04229	0.12792
0.04183	0.13104
0.04110	0.13416
0.04036	0.13728
0.03956	0.14040
0.03887	0.14352
0.03819	0.14664
0.03718	0.14976
0.03616	0.15288
0.03520	0.15600
0.03451	0.15912
0.03379	0.16224
0.03316	0.16536
0.03239	0.16848
0.03166	0.17160
0.03114	0.17472
0.03069	0.17784
0.03019	0.18096
0.02941	0.18408
0.02870	0.18720
0.02791	0.19032
0.02724	0.19344
0.02653	0.19656
0.02565	0.19968
0.02470	0.20280
0.02381	0.20592
0.02315	0.20904
0.02242	0.21216
0.02176	0.21528
0.02100	0.21840
0.02027	0.22152
0.01968	0.22464
0.01913	0.22776
0.01854	0.23088
0.01779	0.23400
0.01708	0.23712
0.01631	0.24024
0.01564	0.24336
0.01492	0.24648
0.01411	0.24960
0.01328	0.25272
0.01247	0.25584
0.01177	0.25896
0.01106	0.26208
0.01037	0.26520

0.00964	0.26832
0.00892	0.27144
0.00826	0.27456
0.00761	0.27768
0.00694	0.28080
0.00622	0.28392
0.00549	0.28704
0.00476	0.29016
0.00404	0.29328
0.00333	0.29640
0.00281	0.29952
0.00258	0.30264
0.00234	0.30576
0.00210	0.30888
0.00184	0.31200
0.00154	0.31512
0.00115	0.31824
0.00060	0.32136
0.00000	0.32448
0.00000	0.32760

TABLE II-B

OPERATION

OF

VALVE NO. 2

A= 2500 FPS

TAU	TIME
1.00000	0.00000
0.19691	0.00250
0.13654	0.00500
0.11045	0.00750
0.09501	0.01000
0.08532	0.01250
0.07799	0.01500
0.07218	0.01750
0.06744	0.02000
0.06691	0.02250
0.06674	0.02500
0.06657	0.02750
0.06648	0.03000
0.06587	0.03250
0.06532	0.03500
0.06478	0.03750
0.06416	0.04000
0.06350	0.04250
0.06254	0.04500
0.06159	0.04750
0.06049	0.05000
0.05996	0.05250
0.05932	0.05500
0.05868	0.05750
0.05815	0.06000
0.05767	0.06250
0.05740	0.06500
0.05713	0.06750
0.05707	0.07000
0.05648	0.07250
0.05592	0.07500
0.05537	0.07750
0.05477	0.08000
0.05401	0.08250
0.05317	0.08500
0.05233	0.08750
0.05126	0.09000

0.05068	0.09250
0.05010	0.09500
0.04947	0.09750
0.04890	0.10000
0.04849	0.10250
0.04814	0.10500
0.04778	0.10750
0.04768	0.11000
0.04709	0.11250
0.04650	0.11500
0.04599	0.11750
0.04539	0.12000
0.04467	0.12250
0.04387	0.12500
0.04307	0.12750
0.04206	0.13000
0.04152	0.13250
0.04095	0.13500
0.04030	0.13750
0.03977	0.14000
0.03926	0.14250
0.03890	0.14500
0.03850	0.14750
0.03836	0.15000
0.03774	0.15250
0.03714	0.15500
0.03666	0.15750
0.03599	0.16000
0.03537	0.16250
0.03458	0.16500
0.03387	0.16750
0.03293	0.17000
0.03235	0.17250
0.03181	0.17500
0.03115	0.17750
0.03067	0.18000
0.03013	0.18250
0.02972	0.18500
0.02926	0.18750
0.02901	0.19000
0.02845	0.19250
0.02784	0.19500
0.02732	0.19750
0.02666	0.20000
0.02605	0.20250
0.02535	0.20500
0.02467	0.20750
0.02383	0.21000
0.02324	0.21250

0.02269	0.21500
0.02209	0.21750
0.02158	0.22000
0.02102	0.22250
0.02053	0.22500
0.02006	0.22750
0.01970	0.23000
0.01914	0.23250
0.01856	0.23500
0.01799	0.23750
0.01738	0.24000
0.01678	0.24250
0.01613	0.24500
0.01548	0.24750
0.01474	0.25000
0.01417	0.25250
0.01359	0.25500
0.01303	0.25750
0.01247	0.26000
0.01193	0.26250
0.01140	0.26500
0.01089	0.26750
0.01043	0.27000
0.00985	0.27250
0.00929	0.27500
0.00870	0.27750
0.00812	0.28000
0.00751	0.28250
0.00692	0.28500
0.00630	0.28750
0.00567	0.29000
0.00511	0.29250
0.00452	0.29500
0.00397	0.29750
0.00339	0.30000
0.00284	0.30250
0.00228	0.30500
0.00213	0.30750
0.00199	0.31000
0.00181	0.31250
0.00162	0.31500
0.00139	0.31750
0.00110	0.32000
0.00071	0.32250
0.00000	0.32500

TABLE II-C

OPERATION

OF

VALVE NO. 2

A= 3000 FPS

TAU	TIME
1.00000	0.00000
0.19762	0.00208
0.13655	0.00416
0.11069	0.00624
0.09535	0.00832
0.08558	0.01040
0.07833	0.01248
0.07258	0.01456
0.06789	0.01664
0.06732	0.01872
0.06740	0.02080
0.06726	0.02288
0.06720	0.02496
0.06685	0.02704
0.06626	0.02912
0.06576	0.03120
0.06525	0.03328
0.06489	0.03536
0.06382	0.03744
0.06305	0.03952
0.06215	0.04160
0.06153	0.04368
0.06117	0.04576
0.06067	0.04784
0.06019	0.04992
0.05957	0.05200
0.05959	0.05408
0.05935	0.05616
0.05932	0.05824
0.05894	0.06032
0.05831	0.06240
0.05781	0.06448
0.05737	0.06656
0.05699	0.06864
0.05606	0.07072
0.05532	0.07280
0.05442	0.07488

0.05381	0.07696
0.05350	0.07904
0.05301	0.08112
0.05248	0.08320
0.05194	0.08528
0.05178	0.08736
0.05158	0.08944
0.05148	0.09152
0.05116	0.09360
0.05049	0.09568
0.04999	0.09776
0.04955	0.09984
0.04911	0.10192
0.04834	0.10400
0.04759	0.10608
0.04674	0.10816
0.04611	0.11024
0.04578	0.11232
0.04534	0.11440
0.04482	0.11648
0.04434	0.11856
0.04410	0.12064
0.04385	0.12272
0.04370	0.12480
0.04335	0.12688
0.04277	0.12896
0.04222	0.13104
0.04177	0.13312
0.04128	0.13520
0.04056	0.13728
0.03985	0.13936
0.03912	0.14144
0.03851	0.14352
0.03812	0.14560
0.03768	0.14768
0.03715	0.14976
0.03668	0.15184
0.03644	0.15392
0.03616	0.15600
0.03591	0.15808
0.03554	0.16016
0.03497	0.16224
0.03448	0.16432
0.03402	0.16640
0.03354	0.16848
0.03283	0.17056
0.03216	0.17264
0.03148	0.17472
0.03093	0.17680

0.03053	0.17888
0.03001	0.18096
0.02954	0.18304
0.02907	0.18512
0.02878	0.18720
0.02849	0.18928
0.02819	0.19136
0.02773	0.19344
0.02718	0.19552
0.02676	0.19760
0.02627	0.19968
0.02578	0.20176
0.02513	0.20384
0.02448	0.20592
0.02385	0.20800
0.02337	0.21008
0.02295	0.21216
0.02242	0.21424
0.02195	0.21632
0.02148	0.21840
0.02114	0.22048
0.02080	0.22256
0.02048	0.22464
0.02000	0.22672
0.01947	0.22880
0.01902	0.23088
0.01854	0.23296
0.01805	0.23504
0.01745	0.23712
0.01688	0.23920
0.01626	0.24128
0.01578	0.24336
0.01534	0.24544
0.01483	0.24752
0.01438	0.24960
0.01391	0.25168
0.01352	0.25376
0.01310	0.25584
0.01276	0.25792
0.01227	0.26000
0.01176	0.26208
0.01130	0.26416
0.01081	0.26624
0.01032	0.26832
0.00977	0.27040
0.00925	0.27248
0.00869	0.27456
0.00822	0.27664
0.00776	0.27872

0.00728	0.28080
0.00681	0.28288
0.00633	0.28496
0.00591	0.28704
0.00546	0.28912
0.00502	0.29120
0.00455	0.29328
0.00405	0.29536
0.00357	0.29744
0.00309	0.29952
0.00261	0.30160
0.00210	0.30368
0.00183	0.30576
0.00168	0.30784
0.00152	0.30992
0.00136	0.31200
0.00117	0.31408
0.00094	0.31616
0.00066	0.31824
0.00027	0.32032
0.00000	0.32240

TABLE III-A

OPERATION

OF

VALVE NO. 4

A= 2000 FPS

TAU	TIME
0.00000	0.00000
0.00008	0.00312
0.00016	0.00624
0.00024	0.00936
0.00032	0.01248
0.00039	0.01560
0.00047	0.01872
0.00054	0.02184
0.00062	0.02496
0.00077	0.02808
0.00091	0.03120
0.00106	0.03432
0.00121	0.03744
0.00135	0.04056
0.00150	0.04368
0.00165	0.04680
0.00180	0.04992
0.00194	0.05304
0.00209	0.05616
0.00224	0.05928
0.00239	0.06240
0.00253	0.06552
0.00268	0.06864
0.00282	0.07176
0.00297	0.07488
0.00312	0.07800
0.00326	0.08112
0.00341	0.08424
0.00355	0.08736
0.00370	0.09048
0.00384	0.09360
0.00399	0.09672
0.00413	0.09984
0.00427	0.10296
0.00442	0.10608
0.00362	0.10920
0.00471	0.11232

0.00486	0.11544
0.00500	0.11856
0.00514	0.12168
0.00529	0.12480
0.00543	0.12792
0.00558	0.13104
0.00572	0.13416
0.00586	0.13728
0.00600	0.14040
0.00615	0.14352
0.00629	0.14664
0.00643	0.14976
0.00658	0.15288
0.00672	0.15600
0.00687	0.15912
0.00701	0.16224
0.00715	0.16536
0.00730	0.16848
0.00744	0.17160
0.00758	0.17472
0.00773	0.17784
0.00787	0.18096
0.00801	0.18408
0.00815	0.18720
0.00829	0.19032
0.00843	0.19344
0.00858	0.19656
0.00872	0.19968
0.00886	0.20280
0.00900	0.20592
0.00915	0.20904
0.00929	0.21216
0.00943	0.21528
0.00958	0.21840
0.00972	0.22152
0.00986	0.22464
0.01000	0.22776
0.01014	0.23088
0.01028	0.23400
0.01042	0.23712
0.01056	0.24024
0.01085	0.24648
0.01099	0.24960
0.01113	0.25272
0.01127	0.25584
0.01142	0.25896
0.01156	0.26208
0.01170	0.26520
0.01184	0.26832

0.01199	0.27144
0.01213	0.27456
0.01227	0.27768
0.01241	0.28080
0.01255	0.28392
0.01269	0.28704
0.01283	0.29016
0.01297	0.29328
0.01311	0.29640
0.01325	0.29952
0.01339	0.30264
0.01348	0.30576
0.01356	0.30888
0.01363	0.31200
0.01368	0.31512
0.01374	0.31824
0.01396	0.32136
0.01386	0.32448
0.01392	0.32760
0.01396	0.33072
0.01696	0.40697
0.02026	0.48322
0.02379	0.55947
0.02771	0.63572
0.03195	0.71197
0.03673	0.78822
0.04203	0.86447
0.04818	0.94072
0.05526	1.01697
0.06391	1.09322
0.06251	1.16947
0.06123	1.24572
0.06000	1.32197
0.05888	1.39822
0.05779	1.47447
0.05679	1.55072
0.05582	1.62697
0.05493	1.70322
0.05407	1.77947
0.05327	1.85572
0.05246	1.93197
0.05178	2.00822
0.05139	2.08447
0.05126	2.16072
0.05166	2.23697
0.05274	2.31322
0.05527	2.38947
0.06078	2.46572
0.07635	2.54197

1.00000	2.61822
0.23498	2.63382
0.23141	2.64942
0.22787	2.66502
0.22434	2.68062
0.22086	2.69622
0.21739	2.71182
0.21394	2.72742
0.21053	2.74302
0.20713	2.75862
0.20374	2.77422
0.20039	2.78982
0.19708	2.80542
0.19377	2.82102
0.19048	2.83662
0.18721	2.85222
0.18396	2.86782
0.18073	2.88342
0.17752	2.89902
0.17433	2.91462
0.17115	2.93022
0.16800	2.94582
0.16486	2.96142
0.16174	2.97702
0.15863	2.99262
0.15553	3.00822
0.15247	3.02382
0.14940	3.03942
0.14635	3.05502
0.14333	3.07062
0.14031	3.08622
0.13729	3.10182
0.13431	3.11742
0.13133	3.13302
0.12836	3.14862
0.12540	3.16422
0.12246	3.17982
0.11952	3.19542
0.11660	3.21102
0.11368	3.22662
0.11078	3.24222
0.10789	3.25782
0.10501	3.27342
0.10214	3.28902
0.09928	3.30462
0.09642	3.32022
0.09358	3.33582
0.09074	3.35142
0.08790	3.36702

0.08508	3.38262
0.08227	3.39822
0.07946	3.41382
0.07666	3.42942
0.07387	3.44502
0.07107	3.46062
0.06829	3.47622
0.06552	3.49182
0.06275	3.50742
0.05998	3.52302
0.05722	3.53862
0.05446	3.55422
0.05171	3.56982
0.04896	3.58542
0.04622	3.60102
0.04348	3.61662
0.04075	3.63222
0.03802	3.64782
0.03529	3.66342
0.03256	3.67902
0.02984	3.69462
0.02712	3.71022
0.02440	3.72582
0.02168	3.74142
0.01897	3.75702
0.01626	3.77262
0.01355	3.78822
0.01084	3.80382
0.00813	3.81942
0.00542	3.83502
0.00271	3.85062
0.00139	3.86622
0.00000	3.88182

TABLE III-B

OPERATION

OF

VALVE NO. 4

A= 2500 FPS

TAU	TIME
0.00000	0.00000
0.00006	0.00250
0.00013	0.00500
0.00019	0.00750
0.00026	0.01000
0.00032	0.01250
0.00038	0.01500
0.00044	0.01750
0.00050	0.02000
0.00061	0.02250
0.00073	0.02500
0.00085	0.02750
0.00097	0.03000
0.00109	0.03250
0.00120	0.03500
0.00132	0.03750
0.00144	0.04000
0.00156	0.04250
0.00168	0.04500
0.00179	0.04750
0.00191	0.05000
0.00203	0.05250
0.00215	0.05500
0.00227	0.05750
0.00238	0.06000
0.00250	0.06250
0.00261	0.06500
0.00273	0.06750
0.00285	0.07000
0.00296	0.07250
0.00308	0.07500
0.00320	0.07750
0.00331	0.08000
0.00343	0.08250
0.00355	0.08500
0.00366	0.08750
0.00378	0.09000

0.00390	0.09250
0.00401	0.09500
0.00413	0.09750
0.00425	0.10000
0.00436	0.10250
0.00448	0.10500
0.00459	0.10750
0.00471	0.11000
0.00482	0.11250
0.00494	0.11500
0.00505	0.11750
0.00517	0.12000
0.00528	0.12250
0.00540	0.12500
0.00552	0.12750
0.00563	0.13000
0.00575	0.13250
0.00586	0.13500
0.00598	0.13750
0.00609	0.14000
0.00621	0.14250
0.00632	0.14500
0.00643	0.14750
0.00655	0.15000
0.00666	0.15250
0.00678	0.15500
0.00689	0.15750
0.00701	0.16000
0.00712	0.16250
0.00724	0.16500
0.00735	0.16750
0.00747	0.17000
0.00758	0.17250
0.00770	0.17500
0.00781	0.17750
0.00793	0.18000
0.00804	0.18250
0.00815	0.18500
0.00826	0.18750
0.00838	0.19000
0.00849	0.19250
0.00860	0.19500
0.00872	0.19750
0.00883	0.20000
0.00895	0.20250
0.00906	0.20500
0.00917	0.20750
0.00929	0.21000
0.00940	0.21250

0.00952	0.21500
0.00963	0.21750
0.00974	0.22000
0.00986	0.22250
0.00997	0.22500
0.01008	0.22750
0.01019	0.23000
0.01031	0.23250
0.01042	0.23500
0.01053	0.23750
0.01065	0.24000
0.01076	0.24250
0.01088	0.24500
0.01099	0.24750
0.01111	0.25000
0.01122	0.25250
0.01133	0.25500
0.01145	0.25750
0.01156	0.26000
0.01167	0.26250
0.01179	0.26500
0.01189	0.26750
0.01201	0.27000
0.01212	0.27250
0.01223	0.27500
0.01234	0.27750
0.01246	0.28000
0.01257	0.28250
0.01269	0.28500
0.01280	0.28750
0.01292	0.29000
0.01303	0.29250
0.01315	0.29500
0.01326	0.29750
0.01337	0.30000
0.01348	0.30250
0.01359	0.30500
0.01364	0.30750
0.01368	0.31000
0.01372	0.31250
0.01377	0.31500
0.01381	0.31750
0.01386	0.32000
0.01391	0.32250
0.01395	0.32500
0.01637	0.38600
0.01898	0.44700
0.02177	0.50800
0.02483	0.56900

0.02813	0.63000
0.03180	0.69100
0.03584	0.75200
0.04046	0.81300
0.04568	0.87400
0.05189	0.93500
0.05121	0.99600
0.05058	1.05700
0.04995	1.11800
0.04937	1.17900
0.04879	1.24000
0.04826	1.30100
0.04772	1.36200
0.04723	1.42300
0.04674	1.48400
0.04628	1.54500
0.04593	1.60600
0.04571	1.66700
0.04575	1.72800
0.04607	1.78900
0.04689	1.85000
0.04843	1.91100
0.05142	1.97200
0.05745	2.03300
0.07352	2.09400
1.00000	2.15500
0.21148	2.16750
0.20837	2.18000
0.20527	2.19250
0.20220	2.20500
0.19913	2.21750
0.19610	2.23000
0.19307	2.24250
0.19007	2.25500
0.18708	2.26750
0.18411	2.28000
0.18116	2.29250
0.17822	2.30500
0.17530	2.31750
0.17238	2.33000
0.16949	2.34250
0.16661	2.35500
0.16375	2.36751
0.16090	2.38001
0.15805	2.39251
0.15523	2.40501
0.15241	2.41751
0.14962	2.43001
0.14682	2.44251

0.14405	2.45501
0.14128	2.46751
0.13852	2.48001
0.13578	2.49251
0.13306	2.50501
0.13032	2.51751
0.12761	2.53001
0.12491	2.54251
0.12222	2.55501
0.11954	2.56751
0.11686	2.58001
0.11419	2.59251
0.11154	2.60501
0.10889	2.61751
0.10624	2.63001
0.10361	2.64251
0.10099	2.65501
0.09837	2.66751
0.09576	2.68001
0.09316	2.69252
0.09057	2.70502
0.08797	2.71752
0.08539	2.73002
0.08282	2.74252
0.08024	2.75502
0.07768	2.76752
0.07512	2.78002
0.07256	2.79252
0.07001	2.80502
0.06747	2.81752
0.06493	2.83002
0.06240	2.84252
0.05987	2.85502
0.05734	2.86752
0.05482	2.88002
0.05230	2.89252
0.04979	2.90502
0.04728	2.91752
0.04477	2.93002
0.04226	2.94252
0.03976	2.95502
0.03727	2.96752
0.03477	2.98002
0.03228	2.99253
0.02978	3.00502
0.02730	3.01753
0.02481	3.03003
0.02232	3.04253
0.01984	3.05503

0.01736	3.06753
0.01487	3.08003
0.01239	3.09253
0.00991	3.10503
0.00743	3.11753
0.00496	3.13003
0.00248	3.14253
0.00129	3.15503
0.00000	3.16753

TABLE III-C

OPERATION

OF

VALVE NO. 4

A= 3000 FPS

TAU	TIME
0.00000	0.00000
0.00005	0.00208
0.00010	0.00416
0.00016	0.00624
0.00021	0.00832
0.00026	0.01040
0.00031	0.01248
0.00036	0.01456
0.00041	0.01664
0.00051	0.01872
0.00061	0.02080
0.00071	0.02288
0.00081	0.02496
0.00091	0.02704
0.00101	0.02912
0.00110	0.03120
0.00120	0.03328
0.00130	0.03536
0.00140	0.03744
0.00150	0.03952
0.00159	0.04160
0.00169	0.04368
0.00179	0.04576
0.00189	0.04784
0.00199	0.04992
0.00209	0.05200
0.00218	0.05408
0.00228	0.05616
0.00238	0.05824
0.00248	0.06032
0.00257	0.06240
0.00267	0.06448
0.00277	0.06656
0.00287	0.06864
0.00296	0.07072
0.00306	0.07280
0.00316	0.07488

0.00326	0.07696
0.00335	0.07904
0.00345	0.08112
0.00355	0.08320
0.00364	0.08528
0.00374	0.08736
0.00384	0.08944
0.00393	0.09152
0.00403	0.09360
0.00413	0.09568
0.00422	0.09776
0.00432	0.09984
0.00442	0.10192
0.00451	0.10400
0.00461	0.10608
0.00471	0.10816
0.00480	0.11024
0.00490	0.11232
0.00500	0.11440
0.00509	0.11648
0.00519	0.11856
0.00528	0.12064
0.00538	0.12272
0.00548	0.12480
0.00557	0.12688
0.00567	0.12896
0.00576	0.13104
0.00586	0.13312
0.00595	0.13520
0.00605	0.13728
0.00615	0.13936
0.00624	0.14144
0.00634	0.14352
0.00643	0.14560
0.00653	0.14768
0.00663	0.14976
0.00672	0.15184
0.00682	0.15392
0.00691	0.15600
0.00701	0.15808
0.00710	0.16016
0.00720	0.16224
0.00729	0.16432
0.00739	0.16640
0.00748	0.16848
0.00758	0.17056
0.00767	0.17264
0.00777	0.17472
0.00787	0.17680

0.00796	0.17888
0.00806	0.18096
0.00815	0.18304
0.00825	0.18512
0.00834	0.18720
0.00843	0.18928
0.00853	0.19136
0.00862	0.19344
0.00872	0.19552
0.00881	0.19760
0.00891	0.19968
0.00900	0.20176
0.00910	0.20384
0.00919	0.20592
0.00929	0.20800
0.00938	0.21008
0.00948	0.21216
0.00957	0.21424
0.00967	0.21632
0.00976	0.21840
0.00986	0.22048
0.00995	0.22256
0.01004	0.22464
0.01014	0.22672
0.01023	0.22880
0.01033	0.23088
0.01042	0.23296
0.01052	0.23504
0.01061	0.23712
0.01071	0.23920
0.01080	0.24128
0.01090	0.24336
0.01099	0.24544
0.01109	0.24752
0.01118	0.24960
0.01128	0.25168
0.01137	0.25376
0.01146	0.25584
0.01155	0.25792
0.01165	0.26000
0.01174	0.26208
0.01184	0.26416
0.01193	0.26624
0.01202	0.26832
0.01212	0.27040
0.01222	0.27248
0.01231	0.27456
0.01241	0.27664
0.01250	0.27872

0.01260	0.28080
0.01269	0.28288
0.01279	0.28496
0.01288	0.28704
0.01297	0.28912
0.01306	0.29120
0.01315	0.29328
0.01325	0.29536
0.01334	0.29744
0.01344	0.29952
0.01353	0.30160
0.01363	0.30368
0.01369	0.30576
0.01373	0.30784
0.01377	0.30992
0.01380	0.31200
0.01384	0.31408
0.01387	0.31616
0.01391	0.31824
0.01394	0.32032
0.01395	0.32240
0.01599	0.37323
0.01818	0.42406
0.02052	0.47489
0.02306	0.52572
0.02581	0.57655
0.02885	0.62738
0.03218	0.67821
0.03594	0.72904
0.04019	0.77987
0.04515	0.83070
0.04475	0.88153
0.04437	0.93236
0.04400	0.98319
0.04365	1.03402
0.04329	1.08485
0.04296	1.13568
0.04262	1.18651
0.04231	1.23734
0.04199	1.28817
0.04170	1.33900
0.04163	1.38983
0.04169	1.44066
0.04200	1.49149
0.04261	1.54232
0.04371	1.59315
0.04556	1.64398
0.04885	1.69481
0.05522	1.74564

0.07161	1.79647
1.00000	1.84730
0.19387	1.85770
0.19107	1.86810
0.18829	1.87850
0.18553	1.88890
0.18278	1.89930
0.18005	1.90970
0.17732	1.92010
0.17462	1.93050
0.17193	1.94090
0.16924	1.95130
0.16657	1.96170
0.16391	1.97210
0.16126	1.98250
0.15863	1.99290
0.15601	2.00330
0.15339	2.01370
0.15080	2.02410
0.14820	2.03450
0.14562	2.04490
0.14305	2.05530
0.14049	2.06570
0.13793	2.07610
0.13539	2.08650
0.13286	2.09690
0.13034	2.10730
0.12782	2.11770
0.12531	2.12810
0.12281	2.13850
0.12032	2.14890
0.11784	2.15930
0.11536	2.16970
0.11290	2.18010
0.11043	2.19050
0.10798	2.20090
0.10554	2.21130
0.10310	2.22170
0.10066	2.23210
0.09823	2.24250
0.09582	2.25290
0.09341	2.26330
0.09100	2.27370
0.08859	2.28410
0.08619	2.29450
0.08381	2.30490
0.08142	2.31530
0.07904	2.32570
0.07666	2.33610

0.07429	2.34650
0.07192	2.35690
0.06956	2.36730
0.06720	2.37770
0.06484	2.38810
0.06249	2.39850
0.06015	2.40890
0.05781	2.41930
0.05546	2.42970
0.05313	2.44010
0.05080	2.45050
0.04847	2.46090
0.04614	2.47130
0.04382	2.48170
0.04149	2.49210
0.03918	2.50250
0.03686	2.51290
0.03455	2.52330
0.03223	2.53370
0.02992	2.54410
0.02761	2.55450
0.02531	2.56490
0.02300	2.57530
0.02070	2.58570
0.01839	2.59610
0.01609	2.60650
0.01379	2.61690
0.01149	2.62730
0.00919	2.63770
0.00689	2.64810
0.00460	2.65850
0.00230	2.66890
0.00121	2.67930
0.00000	2.68970

TABLE IV-A

OPERATION

OF

VALVE NO. 6

A= 2000 FPS

TAU	TIME
1.00000	0.33072
1.00000	0.40697
1.00000	0.48322
1.00000	0.55947
1.00000	0.63572
1.00000	0.71197
1.00000	0.78822
1.00000	0.86447
1.00000	0.94072
1.00000	1.01697
1.00000	1.09322
0.03953	1.16947
0.02796	1.24572
0.02284	1.32197
0.01978	1.39822
0.01769	1.47447
0.01615	1.55072
0.01495	1.62697
0.01399	1.70322
0.01319	1.77947
0.01251	1.85572
0.01251	1.93197
0.01251	2.00822
0.01251	2.08447
0.01251	2.16072
0.01251	2.23697
0.01251	2.31322
0.01251	2.38947
0.01251	2.46572
0.01251	2.54197
0.01251	2.61822

TABLE IV-B
OPERATION
OF
VALVE NO. 6
A= 2500 FPS

TAU	TIME
1.00000	0.32500
1.00000	0.38600
1.00000	0.44700
1.00000	0.50800
1.00000	0.56900
1.00000	0.63000
1.00000	0.69100
1.00000	0.75200
1.00000	0.81300
1.00000	0.87400
1.00000	0.93500
0.03953	0.99600
0.02796	1.05700
0.02284	1.11800
0.01978	1.17900
0.01769	1.24000
0.01615	1.30100
0.01495	1.36200
0.01399	1.42300
0.01319	1.48400
0.01251	1.54500
0.01251	1.60600
0.01251	1.66700
0.01251	1.72800
0.01251	1.78900
0.01251	1.85000
0.01251	1.91100
0.01251	1.97200
0.01251	2.03300
0.01251	2.09400
0.01251	2.15500

TABLE IV-C

OPERATION

OF

VALVE NO. 6

A= 3000 FPS

TAU	TIME
1.00000	0.32240
1.00000	0.37323
1.00000	0.42406
1.00000	0.47489
1.00000	0.52572
1.00000	0.57655
1.00000	0.62738
1.00000	0.67821
1.00000	0.72904
1.00000	0.77987
1.00000	0.83070
0.03953	0.88153
0.02796	0.93236
0.02284	0.98319
0.01978	1.03402
0.01769	1.08485
0.01615	1.13568
0.01495	1.18651
0.01399	1.23734
0.01319	1.28817
0.01251	1.33900
0.01251	1.38983
0.01251	1.44066
0.01251	1.49149
0.01251	1.54232
0.01251	1.59315
0.01251	1.64398
0.01251	1.69481
0.01251	1.74564
0.01251	1.79647
0.01251	1.84730

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