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A STUDY OF COLUMN SEPARATION ACCOMPANYING TRANSIENT FLOW OF LIQUIDS IN PIPES

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SYMBOLS

Symbols	Units	Descriptive Identification
A	$ft.^2$	Cross sectional area, pipe flowing full
A	$ft.^2$	Cross segmental area, pipe flowing partially full
a	ft./sec.	Celerity of transient pressure pulse, pipe flowing full
a		Subscript denoting ambient condition
b	ft.	Outside pipe radius
C+, C-		Characteristics curves
C_1, C_2, C_3, c'		Constants of integration
c, c_1, c_2, c_3		Coefficients of pipe support and restraint
c		Subscript denoting circumferential direction
D	ft.	Inside pipe diameter
E	$lb./ft.^2$	Modulus of Elasticity of pipe wall
e, exp		Napierian base
f		Darcy-Weisbach frictional resistance term
f		Function notation
g	$ft./sec.^2$	Acceleration of gravity
g		Subscript denoting gaseous condition
H	ft.	Piezometric head ($P/\rho g + z$)
H		Coordinate axis
H_f	ft.	Head loss due to resistance to flow
i		Counting integer or indexing subscript
J	ft.lb.	Parameter denoting air mass in bubble
K	$lb./ft.^2$	Bulk modulus of elasticity of liquid
k		Counting integer or indexing subscript; usually refers to pipe segment

SYMBOLS (Cont'd)

Symbols	Units	Descriptive Identification
L		Left grid point on x,t plane; frequently used as subscript
L		Length of an undefined pipe segment
M		Middle grid point on x,t plane; frequently used as subscript
m	$sec.^{-1}$	Linear multiplier coefficient $\pm\sqrt{A/gT}$; pipe flowing partially full
m		Subscript denoting x-position
n	$sec.^{-1}$	Linear multiplier coefficient $\pm g/a$; pipe flowing full
P		Grid point and intersection point of characteristics curves on x,t plane; frequently used as subscript
P_w	ft.	Wetted perimeter; pipe flowing partially full
p	$lb./ft.^2$	Internal pipe pressure
p	$lb./ft.^2$	Internal bubble pressure
p		Subscript, denotes x-length of parabolic void
q	$lb./ft.^2$	External pressure on pipe
R		Right grid point on x,t plane; frequently used as subscript
R	ft.	Inside pipe radius
R	ft.lb./lb./Deg.	Gas constant for air
R_H	ft.	Hydraulic radius; pipe flowing partially full
r	ft.	Radial distance
r	ft.	Cavitation nucleus radius
r		Subscript denoting radial direction
T	ft.	Free surface width; pipe flowing partially full

SYMBOLS (Cont'd)

Symbols	Units	Descriptive Identification
T		Coordinate axis
t	sec.	Time
t		Subscript denoting travel time
u	ft./sec.	Mean velocity; pipe flowing partially full
$\forall$	$ft.^3$	Volume
v	ft./sec.	Mean velocity; pipe flowing full
v		Subscript denoting vapor condition
X		Coordinate axis
x	ft.	Distance measured in longitudinal space direction
Z		Coordinate axis
z	ft.	Depth of flow; pipe flowing partially full
α		Intersection point of C+ and t-grid on x,t plane; frequently used as a subscript
Γ	$ft./sec.^2$	Equation of motion; pipe flowing full
Γ	ft./sec.	Equation of continuity; pipe flowing full
Γ	ft./sec.	Equation of continuity; pipe flowing partially full
Γ	ft./sec.	Equation of motion; pipe flowing partially full
ϵ		Intersection point of C- and t-grid on x,t plane; frequently used as a subscript
η	ft./ft.	Strain
θ		Radial angle subtended by pipe wall element
θ		A decimal parameter
θ		Gradient angle of pipe ($x_x = -\sin\theta$)
Λ	ft./sec.	Linear sum of Γ_3 and Γ_4

SYMBOLS (Cont'd)

μ		Poisson's ratio
ξ	ft.	Radial increment of displacement
ρ	slugs/ft.^{3}	Liquid density
σ	lb./ft.^{2}	Stress
σ	lb./ft.	Surface tension
τ	lb./ft.^{2}	Boundary shear stress at pipe wall
Φ		Coefficient correcting K for changing pressure
φ		Ψ/r
X		Coefficient for change in pipe size
Ψ		Coefficient for change in pipe size
ψ		$\sigma_r r$
Ω	ft./sec.^{2}	Linear sum of Γ_1 and Γ_2
$\mathbb{R}$		Reynolds number

CHAPTER I

INTRODUCTION

Engineering treatment of the phenomenon of the liquid column separation frequently accompanying transient pipe flow has lacked rational interpretation in terms of the governing fluid dynamics. This study of column-separation attempts to provide better insight into the mechanics and dynamics of the phenomenon while establishing a more rational physical basis for its interpretation and analysis.

Description of Problem

Consider the liquid pressure at a point in a pipeline which is flowing full. Should this point pressure decrease, regardless of cause, to the vapor pressure of the flowing liquid, a vapor cavity will form. This vapor cavity is sometimes referred to as a vapor column. The phenomenon of vapor cavity formation is commonly referred to as a "column separation," meaning separation or interruption of the liquid column. It often occurs following rapid closure of a valve in a pipeline which is flowing full. Nevertheless, column separation may also occur under other circumstances, for instance, following propagation of a transient wave of low pressure into an elevated portion of a pipeline flowing full. Such a low-pressure wave, for example, could be caused by a sudden pump failure in a liquid transmission or distribution system. The severe damage which the high pressures associated with collapse of the vapor column can inflict upon the pipe system causes column separation to be a problem of significant engineering concern.

Certain features associated with column separation have been the cause of speculation in the past. The physical laws, for example, governing the shape and movement of the vapor column have not been adequately described. Moreover, the nature of the collapse of such a vapor column is even less well defined. Definition of these physical laws together with a broader understanding of vapor column collapse would be of appreciable aid in providing enlightened engineering design and trouble-free operation of both large and small, closed-conduit, hydraulic systems.

The problem of column separation is clearly an integral part of the much broader problem of transient liquid flow in both open and closed conduits; that is, flow in which the velocities and pressures vary with location and with time. In pipes the phenomenon of transient flow of liquids is commonly referred to by the imprecise, lay term, "water hammer." However, column separation has a unique and distinctive feature which sets it apart from the ordinary water-hammer type phenomenon. In the portion of pipe momentarily occupied by the vapor cavity, any flow of liquid occurring beneath the cavity appears to be free-surface flow, in other words, flow in which gravity would be the principal governing factor. Thus, transient flow conditions occur throughout a system composed of both closed-conduit flow (pipe flowing full) and open-channel flow (pipe flowing partially full). However, in that phase of the problem involving transient, open-channel flow, the pressure variations which occur with time and location are manifested by fluctuations of free surface head (depth of liquid) above a datum.

The motivation for the present study was the belief that pertinent information regarding the various undetermined aspects of column

separation could be qualitatively defined and quantitatively determined through the development of an experimentally-verified, mathematical model simulating transient, liquid, pipe flow with column separation.

Review of Literature

Study of transient flow in both open and closed conduits is not a new area for research in fluid dynamics in any sense of the word. To be sure, water hammer occurring in pipe flow was a topic of interest to many of the noted hydraulicians of the early and middle 19th century. However, rational physical interpretation and true understanding of this closed conduit phenomenon did not evolve until 1898 when Joukowsky[29] published his treatise on the subject. His work, an outgrowth of the experimental studies and mathematical analysis which he conducted while supervising design of the then new Moscow waterworks, provided many of the basic concepts and relationships essential to comprehension and further study of closed conduit, transient flow. Some four years later Allievi[1] expanded and greatly extended Joukowsky's analytic work. However, Allievi did not publish his rather extensive mathematical and graphical treatment of water hammer until 1913. Nevertheless, this work became the truly definitive study from which much of the modern day interpretative analysis of closed conduit, transient flow can be traced.

Meanwhile, during the decades after the mid 19th century, the fraternity of French hydraulicians, among them Saint-Vennet, Dupuit, Bresse, and Boussinesq, were concerning themselves with the analysis of open-channel hydraulics. In 1871 Saint-Vennet[45] presented a paper to the French Academy of Sciences which contained a form of the equation of motion for unsteady flow in open channels. Six years later in 1877 the Academy

published Boussinesq's outstanding essay on hydraulics,[7] the third section of which presents an analysis of wave stability and wave propagation celerity in open channels. Taken together, these contributions provided the foundation necessary for the present day study of transient flow in open conduits.

Although the rudimentary dynamics of transient flow in both open channels and closed conduits had been more or less correctly appraised and partially formulated by the early years of the 20th century, techniques for the analysis of the phenomena still remained to be developed and applied. Drawing extensively upon Allieve's graphical methods, Bergeron[6] and others expanded and applied these techniques in order to approximate solutions for various problems involving electrical, mechanical, as well as fluid transients. It is entirely anachronistic, however, to discover that in 1860, the German mathematician Riemann[41,48,49,60] had already developed and used the then unnamed method of characteristics to achieve an explicit solution of a second order partial differential equation depicting sound-wave propagation in steady, two-dimensional air flow. An interlude of nearly 30 years passed before Massau discovered Riemann's work and transformed his solution into a graphical technique in 1889. Later, in 1900, after extending the graphical technique to apply to first order partial differential equations as well, Massau[36] published a fully-documented study of his application of the method of characteristics. It is of particular interest to note that his presentation included examples specifically treating transient, open-channel flow. Yet, despite Massau's important contribution, the potential value of the method of characteristics as a powerful tool for the explicit solution of problems concerning both open and closed conduit transient flows, remained largely unrecognized.

In fact, the basic physical and mathematical similarity of the two flow situations--the transient, pressure-wave phenomenon in pipes on the one hand and the transient, gravity-wave phenomenon in open channels on the other--was only vaguely appreciated.

Meanwhile, Thomas,[58] in a particularly noteworthy paper, attacked the open-channel, flood-routing problem as truly a problem in transient flow. Starting with the fundamental partial differential equations for unsteady flow, he outlined a tentative procedure for their numerical solution. Stoker, treating the same problem, outlined an implicit procedure[56] based upon an iterative solution of the partial difference equations. Dronkers[15] and Schönfeld,[47] studying the closely related problem of tide-induced, transient flow in estuaries, outlined a solution technique employing power series as well as one based upon characteristics. Chow[10] presented a graphical solution based upon the method of characteristics as first developed by Lin.

However, all of the above-mentioned solution techniques for handling problems in both open and closed conduit transient flow suffer from one common and very serious drawback; namely, an overwhelming amount of very tedious, exacting, and extremely time-consuming computation. This formidable drawback has been all but eliminated within the past decade by the introduction and rapid development of the high speed digital computer and sophisticated computer programming languages. It is now economically practicable as well as technically feasible to solve a great variety of transient flow problems by digital computer techniques as evidenced by the recent technical literature.[4,5,21,30,53,54,55]

During the first half of the 20th century Allieve's analysis of water hammer was refined and the graphical techniques which he and Bergeron had devised were tediously applied to a variety of practical, closed-conduit, transient-flow problems.[2,28,37,39,42,52] It was the treatment of certain of these practical problems which began to focus attention upon the specific phenomenon of liquid column separation and the associated free-surface flow taking place beneath the resulting vapor cavity.[31,43] A search of the literature, however, evidences little actual investigation of the mechanics of column separation in transient flow systems. Recent publications by Li[32,33] and by Walsh[34] are notable exceptions. In 1962 Li presented a theoretical treatment of column separation in a pipe of rectangular cross section with frictionless flow. Although several different separation conditions were considered, cavity behavior was treated as an isolated phenomenon rather than a phenomenon integrally dependent upon the transient flow conditions prevailing throughout the entire conduit system. No experimental verification of the analysis was presented in the paper. The chief result of this study appeared to be that the form of the separation void has little bearing on the magnitude of the resulting pressure decay. Heath[8] also studied column separation accompanying the rapid closure of a valve located at the end of a long pipe. However, flow in the pipe was assumed to be frictionless and an equivalent friction loss was inserted in the graphical analysis.

In a subsequent paper Li and Walsh reported their investigation of the maximum pressure resulting from the collapse of the vapor cavity. Escande[18] treats column separation occurring in a penstock subject to instantaneous valve closure by using graphical means. However, neither

the growth nor the collapse of the vapor cavity, nor the dynamics of the flow beneath the cavity is adequately treated in the investigations mentioned above. What is perhaps more significant is that the cavity resulting from the liquid column separation was not interpreted as a manifestation of free-surface, open-channel, transient flow occurring adjunctly and simultaneously with closed conduit transient flow in the same pipe system.

In recent years considerable interest has developed concerning the dynamic conditions and liquid properties prevailing at the inception of cavitation. As a result of their investigation of the roles of air diffusion and liquid tensile stresses upon incipient cavitation, Parkin and Kermeen[38] have shown that air diffusion in flowing water is responsible for the growth of microscopic bubbles on the solid boundaries in a region where the pressure is slightly greater than vapor pressure. Moreover, the microscopic air bubbles serve as nuclei for the explosive growth of vapor cavities as the pressure decreases, according to Ripken and Killen.[44] Other apparent properties of incipient cavitation are presented by Stepanoff and Kawaguchi[50] and by Hooper.[27]

Scope of Investigation

This study of column separation may be divided into two major phases. The first phase treats the theoretical analysis and analytical interpretation of the problem of transient liquid flow with column separation; the second phase concerns the accompanying experimental investigations.

A theoretical interpretation of the problem of column separation is presented in Chapter II. The fundamental, quasilinear, partial differential equations representing one-dimensional, transient, liquid motion

in pipes as well as in open channels are derived and reviewed in Chapter III. The friction losses encountered in both types of flow are included in the respective sets of equations. Techniques for evaluating these sets of equations, based upon numerical interpretations of the method of characteristics for first-order, hyperbolic, partial differential equations, are also developed and presented in Chapter III.

The two sets of partial differential equations together with the respective evaluation techniques provide the basic building blocks used to formulate the mathematical model simulating transient liquid flow with column separation. Chapter IV is devoted to formulation of this model in terms of an operational program for high-speed digital computer. The functions and operating sequence of the model are presented in a flow chart. The digital computer program together with all major subroutines and supporting programs are presented in Appendices I and II, respectively.

The flow system employed in the second or experimental phase of the study was specifically designed to facilitate the laboratory measurement of column separation. A rapid-closing, solenoid-operated, gate valve was employed in order to produce column separation and to fix its initial occurrence within the system to a face of the gate in the solenoid-operated valve. Although column separation could certainly have been induced at the downstream face of the valve gate, the incipient formation of the vapor cavity would tend to take place while the gate was still in the process of closing. Moreover, flow separation on the downstream face of the gate could seriously disturb the liquid flow pattern. Clearly, these conditions could lead to distortion of the ultimate shape of the vapor cavity. In order to avoid this possibility, a flow system was selected

consisting of a long pipe leading from a constant-level, low-head reservoir to an elevated position. The solenoid gate-valve was situated at the end of an elevated, horizontal section of pipe. A short return pipe connected the valve to a sump. Flow was maintained by syphon action such that column separation would occur without cavity distortion at the upstream face of the gate of the solenoid-operated valve following abrupt valve closure. The separation phenomenon was achieved once the initial wave of high pressure produced at the moment of valve closure had propagated from the valve to reservoir, and the counterpart, low-pressure wave had propagated back to the valve. Water was used as the liquid throughout the laboratory investigation. Column separation was confined to the elevated section of horizontally-mounted pipe. A detailed discussion of the experimental apparatus, of the instrumentation used in measuring column separation, and of the measurements themselves is presented in Chapter V.

In order to acquire specific information about column separation from the mathematical model, it must be activated and numerically evaluated by the digital computer for the particular set of bounding parameters delineating the experimental flow system being investigated in the laboratory. Chapter VI presents a comparison of the analytic and experimental results obtained for various laboratory conditions. A discussion of the findings and some concluding remarks are also contained in Chapter VI. Chapter VII briefly summarizes the principal conclusions derived from the study.

All apparatus used in the experimental phase of the study was assembled and all experimental work conducted in the G. G. Brown Fluids Engineering Laboratory at The University of Michigan. The digital computer

program and associated subroutines were written in MAD, the Michigan Algorithm Decoder language,[3] and executed on an IBM 7090/1410 digital computing system at The University of Michigan Computing Center.

CHAPTER II

THEORETICAL ANALYSIS

Contrary to what one might deduce from literal interpretation of the term "column separation," complete physical interruption of liquid flow in a horizontal pipe does not take place for the magnitudes of transient pressures and velocities ordinarily encountered in horizontal closed conduit fluid systems. In fact, once nascent development of a vapor cavity has occurred at a point in the pipe, the cavity expands and propagates in the direction of flow as an elongated "bubble." A typical example of a vapor cavity resulting from column separation in water flow in a horizontal pipe is shown in Figure 1. While the vapor cavity occupies the upper volume segment within the pipe, liquid continues to flow with a free surface in the lower volume segment.

With identification and recognition of the typical physical circumstances commonly encountered with column separation, two key questions immediately come to mind. These questions are the following:

(a) Once a vapor cavity has formed and the liquid has pulled away from the uppermost, inner surface of the pipe, is not the flow which is occurring beneath the cavity simply free-surface, gravity flow?

(b) If time is measured from the moment of column separation, must not the volume of the vapor cavity at any subsequent instant be equivalent to the accumulated volume of liquid discharged through the pipe just ahead of the cavity?

Deductive reasoning and rational analytic interpretation of the column separation phenomenon seem to indicate that the answer to both of these questions is unquestionably affirmative.

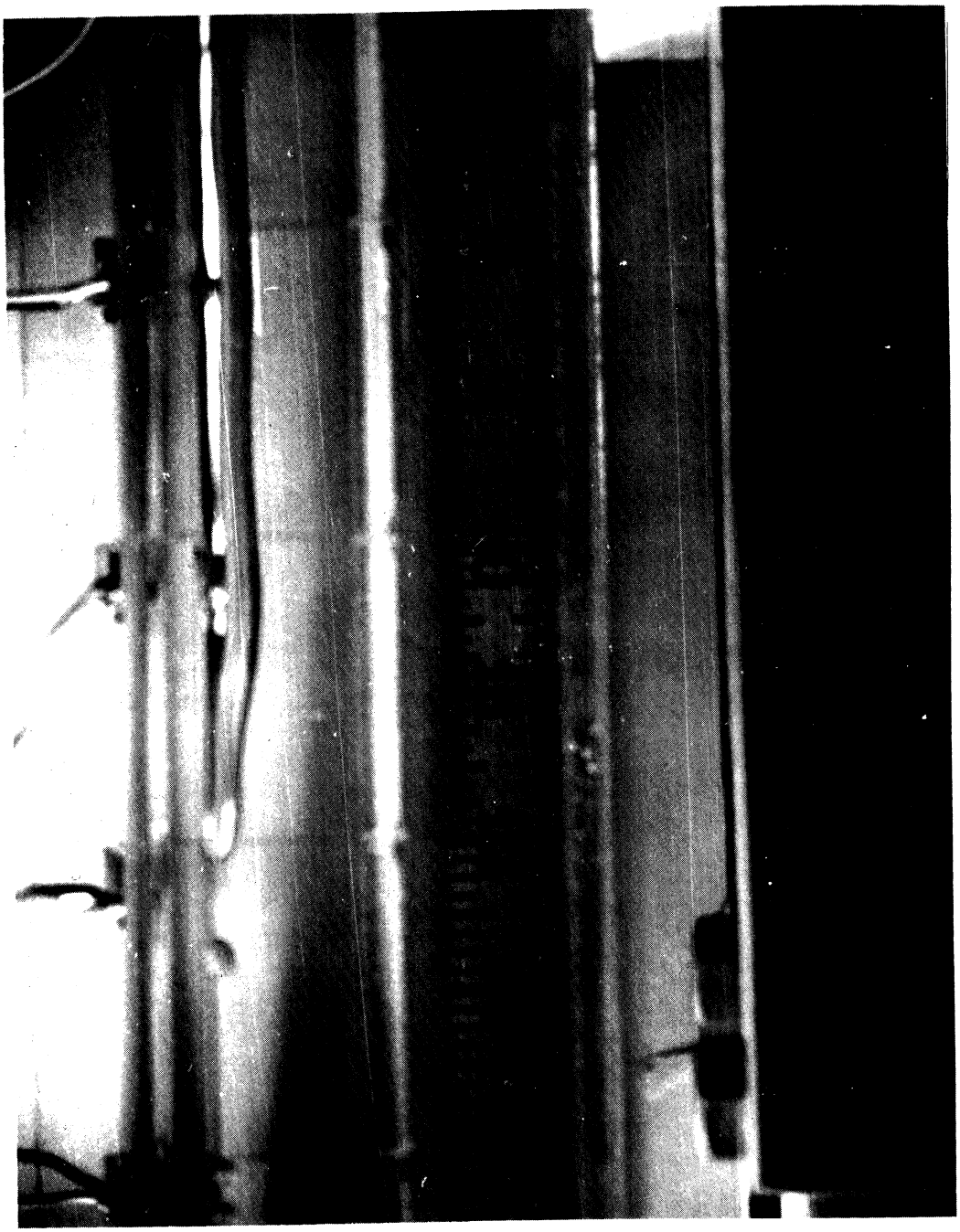

Figure 1. Photograph of a Typical Vapor Cavity Accompanying Column Separation.

Although a surface tension mechanism must appreciably influence the actual separation of the liquid from the inner surface of the pipe wall, the effects of this mechanism can only be very local and temporal at best. Once separation has occurred and a free liquid surface exists, the remaining forces--namely, gravity and fluid friction forces--must be the principal forces acting upon the flow. Of course, the flowing liquid continues to have momentum. Therefore, one may hypothesize that the flow occurring beneath the vapor cavity is simply unsteady, open-channel flow in a circular conduit. More specifically, the free-surface, gravity flow produced by column separation is hypothesized to be analogous to a negative surge wave in an open channel of circular section.

Meanwhile, pipe flow ahead of the vapor cavity is assumed to continue as full-pipe flow. One may further hypothesize that transient conditions continue to govern the flow in this portion of the pipe system. However, the magnitude of the pressure fluctuations must rapidly diminish as a result of the change in the boundary conditions introduced by the vapor cavity. In fact, liquid motion in the portion of the pipe which continues to flow full must approximate surge flow.

By way of illustration consider a reservoir and a quick-closing gate valve connected by a long, horizontal pipe. Let the reservoir be exposed to atmospheric pressure as shown in Figure 2. The mean velocity of flow in the pipe system is v while the pressure is $p = \gamma(h_o - h_f)$ in which γ is the specific weight of the liquid, h_o is the head of liquid i the reservoir, and h_f the head loss created by fluid friction in the pipe. If the gate valve at point C is abruptly closed at time t_o, transient flow conditions are created in the pipe. A positive (high pressure) wave

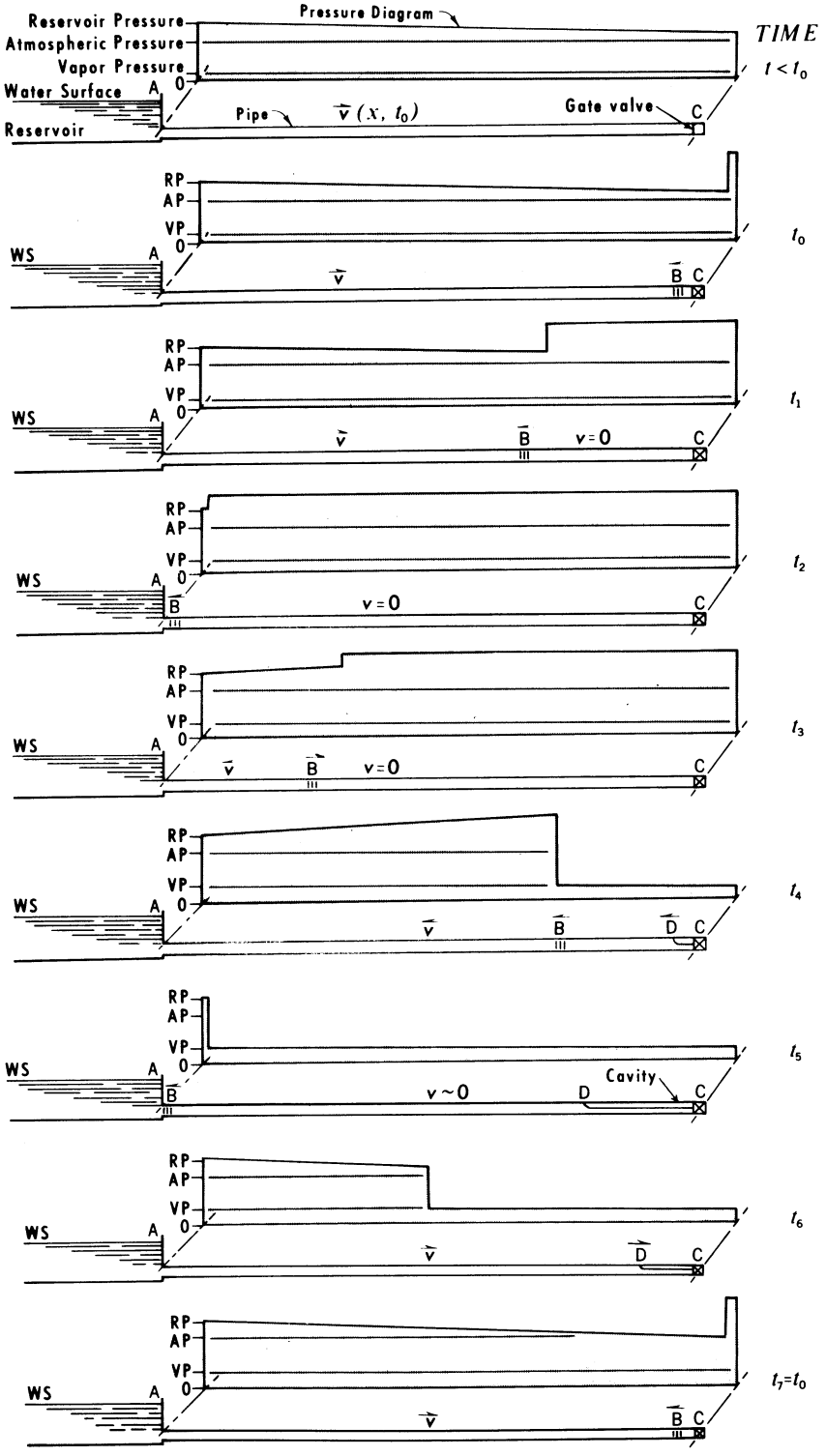

Figure 2. Schematic Time-Sequence Representation of Column Separation and Pressure Pattern in a Pipe System Undergoing Transient Flow.

caused by the rapid deceleration of the liquid propagates from point C toward the reservoir at point A as indicated by the wave front at B . At time t_1 flow from the reservoir continues with undiminished velocity toward B . However, between B and C the velocity is reduced to nearly zero; the pressure, which greatly exceeds p , compresses the liquid and tends to expand and, in some instances, elongate the pipe segment. When the positive pressure wave reaches A at time t_2 , the pressure is abruptly reduced to the sustaining pressure of the reservoir. The compressed liquid in the pipe begins to expand and starts flowing toward A . The pressure between A and B returns to p as the pressure-drop, delimited by the wave front B propagates toward C at time t_3. However, when the pressure drop reaches C , the entire column of liquid, AC , is moving toward A with velocity v . Because the gate at point C remains closed, the water column abruptly decelerates and the pressure decreases below p . A negative (low pressure) wave tends to develop, but because the pressure becomes less than the vapor pressure of the liquid, a vapor cavity is assumed to occur at the uppermost point on the valve gate at C and column separation takes place at time t_4 . The cavity expands until at time t_5 the transient velocity in the segment of pipe flowing full, that is, segment AD , becomes zero. Meanwhile, unsteady, free surface flow has been occurring beneath the cavity in the pipe segment DC . However, the differential pressure between the reservoir and the vapor cavity causes the liquid column, AD , to flow toward C as indicated at time t_6 , thereby initiating the imminent collapse of the vapor cavity. At time t_7 the vapor cavity collapses and conditions in the system are again equivalent to those which occurred at t_0 . The

phenomenon will continue to repeat itself, although diminished in magnitude by the energy losses caused by fluid friction, until the pressure fails to drop below vapor pressure and column separation fails to occur.

The above description of the sequence of physical events--though admittedly somewhat oversimplified and idealized--provides a basic familiarity with the transient-flow, column-separation phenomena as encountered in the experimental system.

A more penetrating and detailed analysis of these phenomena leads one to hypothesize circumstances which could bring about the genesis, growth, and collapse of the vapor cavity anticipated at time t_4 in the above system. Because the causative drop in pressure first takes place at the gate valve, it is reasonable to assume that cavitation will originate at the point of lowest pressure on the upstream face of the valve gate. The actual point of origin is probably at the topmost intersection of the vertical valve gate with the upstream port in the valve itself. As the pressure rapidly drops below atmospheric pressure and approaches the vapor pressure of the water, one or more undissolved microscopic air cavities--air nuclei--attached to the uppermost edge of the gate or to particulate matter in the flow begin to expand. Molecules of free gaseous air coming out of solution in the immediate vicinity of the point of lowest pressure enter the bubble and help to increase its size. Mutual coalescence takes place between adjacent bubbles and the larger resultant bubbles continue to expand until one is of sufficient magnitude that the difference between its internal pressure and the decreasing external pressure is enough to offset the surface-tension pressure which is inversely proportional to its size. Once this threshold size is reached,

the bubble will expand explosively as a water-vapor-filled cavity. Calculations show that the threshold bubble diameter must exceed approximately 8×10^{-4} inches (20 microns) in order for vapor cavity expansion to occur at pressures normally encountered in practical situations. It is quite probable that for a fleeting moment the water undergoes tensile stress (as demonstrated[38] in recent water tunnel experiments) until the nascent bubble can sustain explosive cavitation after which the pressure reverts to the vapor pressure of the liquid water. The complete hypothesized sequence of events, starting with the rapid drop in pressure and concluding with the onset of the explosive growth of the vapor cavity, occurs, of course, in a very brief time span--probably a few milliseconds in duration at most.

During the same time interval in which cavitation is initiated, the horizontal column of water (denoted by AC , Figure 2) starts to undergo deceleration of its flow upstream, toward the reservoir. This deceleration, of which the pressure drop responsible for inception of cavition is but a manifestation, first occurs in the water adjacent to the gate valve. Although the considerable momentum of the water moving as a column tends to cause it to separate from the vertical face of the gate, the change in momentum caused by the deceleration of the flow is ordinarily insufficient to completely overcome gravitational effects. As a result the tendency for column separation at the gate is satisfied by the explosive growth of the nascent air bubble into a water-vapor cavity occupying the topmost segment of the pipe. Gravity causes some of the decelerating flow to remain in the bottom segment of the pipe and in contact

with the gate. The upstream flow in the pipe continues to decelerate as the front of the pressure wave, B , delimiting the drop to vapor pressure propagates toward the reservoir. Meanwhile the vapor cavity, advancing (D) behind this wave front and seemingly tearing the water from the topmost inner surface of the pipe wall, expands to occupy a volume equivalent to the volume vacated by the receding full-pipe flow. Surface tension may have some nominal effect upon the shape of the advancing edge of the cavity.

Ultimately, the forces created by the frictional resistance to flow and by the differential pressure between the reservoir and the vapor cavity bring water column AD to a momentary rest. At the same time the free-surface, transient flow taking place beneath the cavity (DC) gradually diminishes to a minimum. The vapor cavity will achieve its maximum expansion at the moment of rest. But because the differential pressure force continues to act, the water in column AD now reverses direction and begins to flow downstream toward the gate valve. Conditions are now right for collapse of the vapor cavity. As column AD accelerates in the downstream direction, one hypothesizes that the interface between the vapor cavity and the water column becomes a surging, free-surface front. Although surface tension is believed to be a factor of nominal overall effect, it is assumed to aid reattachment of this free surface to the pipe wall. Moreover, the total volume of the cavity decreases at the same rate at which full-pipe flow is occurring at D . At the instant of total collapse of the water-vapor cavity, the abrupt deceleration of the water column by the closed gate valve once again produces high pressures at time t_7 . The minute volume of gaseous air which initiated

cavity formation is readily forced back into solution, and, except for the loss of energy expended to overcome flow friction, conditions in the system at time t_7 are analogous to those at time t_0 .

Now that the theoretical concepts of transient pipe flow with column separation have been hypothesized and explicitly set forth, the analytic conditions believed to describe and govern these phenomena can be ascribed. This is done in the following chapter.

CHAPTER III

ANALYTIC INTERPRETATION AND EVALUATION PROCESS

Derivations of the basic differential equations describing transient liquid motion, first in a pipe flowing full and then in a horizontal pipe flowing partially full, are given in this chapter. Flow is simulated mathematically according to conventional one-dimensional analysis in which the longitudinal space-dimension and time are the independent variables governing analysis.

Several underlying assumptions are needed to provide a foundation and a starting point from which to undertake theoretical analysis of column separation in transient pipe flow. These assumptions concern the physical properties of the liquid, the physical properties of the pipe material, and the kinematics of the flow:

(a) The fluid used in the flow system is elastic and of homogeneous density when in its liquid state.

(b) The minute fluctuations of the liquid vapor pressure, resulting from the latent heat of vaporization and occurring at the instant of vapor-cavity formation or collapse, are insignificant by comparison with the difference between atmospheric pressure and vapor pressure.[33] Therefore, these pressure fluctuations may be, and in fact, are disregarded.

(c) The pipe is constructed of a sectionally homogeneous, isotropic, elastic solid in which the stresses never exceed the yield point of the material.

(d) The velocity and the pressure in the pipe when flowing full are considered to be uniformly distributed over any cross section transverse to the pipe, with the result that the flow may be treated as one-dimensional, closed-conduit flow.

(e) The velocity in the pipe when flowing partially full is considered to be uniformly distributed over any transverse cross segment of flow. Moreover, vertical accelerations of the water surface are considered to be insignificant, implying that hydrostatic pressure prevails, and thereby permitting the flow to be treated as one-dimensional, open-channel flow.

(f) The frictional resistance encountered with transient flow, whether it be in a closed conduit or in an open channel, is assumed to be proportional to some power of the mean velocity in a cross section (or segment) transverse to the flow. The extent to which frictional resistance may be dependent upon the transient character of the flow is believed nominal[14,46] and is disregarded.

(g) Surface tension forces in the regions where the free water surface intersects the solid, pipe-wall boundary are assumed to be of insignificant overall effect and are disregarded. This assumption is somewhat less valid for pipes of small diameter.

In deriving each of the sets of partial differential equations according to the assumptions set forth above, elements of water are considered which are bounded by two fixed planes normal to the longitudinal

axis of flow. Discharge and velocity are assumed to be positive when water is flowing in the positive x direction. A pipe having finite wall thickness is considered in the derivation of the equations describing transient liquid motion in the pipe flowing full. The laws of conservation of mass and conservation of momentum govern the derivation of the equation of continuity and the equation of dynamic equilibrium, respectively, for both regimes of flow.

Once the sets of partial differential equations describing transient liquid motion have been derived, they are recognized to be of the hyperbolic type and are then transformed into sets of total differential equations which are valid along their respective "characteristics" curves. These sets--one set for the pipe flowing full and another for the pipe flowing partially full--are then expressed as sets of finite difference equations readily amenable to solution by high-speed, digital computer. The actual finite difference technique used in developing the computer solution is an adaptation of the specific time interval procedure advanced by Hartree and others.[11,12,19,20,21,25,26,35] Initial values obtained from steady flow conditions, together with expressions for the various boundary conditions encountered at the valve, at junctions between pipes, and at the reservoir make an explicit solution possible.

Equations of Transient Motion--Pipe Flowing Full

Transient motion in a pipe flowing full is a function of two independent variables. These variables are the space and time coordinates, x and t, respectively. Let x be the axial location measured along the pipe from some arbitrarily fixed reference point. Two quasi-linear partial differential equations are written to represent the transient

velocities and pressures in the pipe. Once derived these relationships are transformed into a set of four total differential equations which are the so-called "characteristic" equations. The characteristic equations are subsequently written as finite difference equations after which numerical methods are introduced and a solution technique developed to permit their evaluation by high-speed, electronic digital computer. The appropriate boundary conditions which govern the solution are examined and set forth.

Equation of Continuity

The equation of continuity states that the net mass inflow per unit time into a pipe segment is equal to the time rate of mass increase taking place within the segment. This statement is premised upon the concept of the conservation of mass. A typical control segment of a pipe that is flowing full is shown in Figure 3.

If v is the average velocity and ρ the density of the liquid flowing into the segment (Figure 3) then the mass influx per unit time is ρAv, where A is the cross-sectional area at (1). At cross section (2) the efflux of mass from the segment is given by

$$\rho Av + \frac{\partial(\rho Av)}{\partial x} dx \ .$$

The net mass inflow into the segment is

$$\rho Av - [\rho Av + \frac{\partial(\rho Av)}{\partial x} dx]$$

or

$$- \frac{\partial(\rho Av)}{\partial x} dx \ . \qquad (1)$$

The total mass in the segment is ρAdx. Therefore, the time rate of mass increase occurring within the segment is

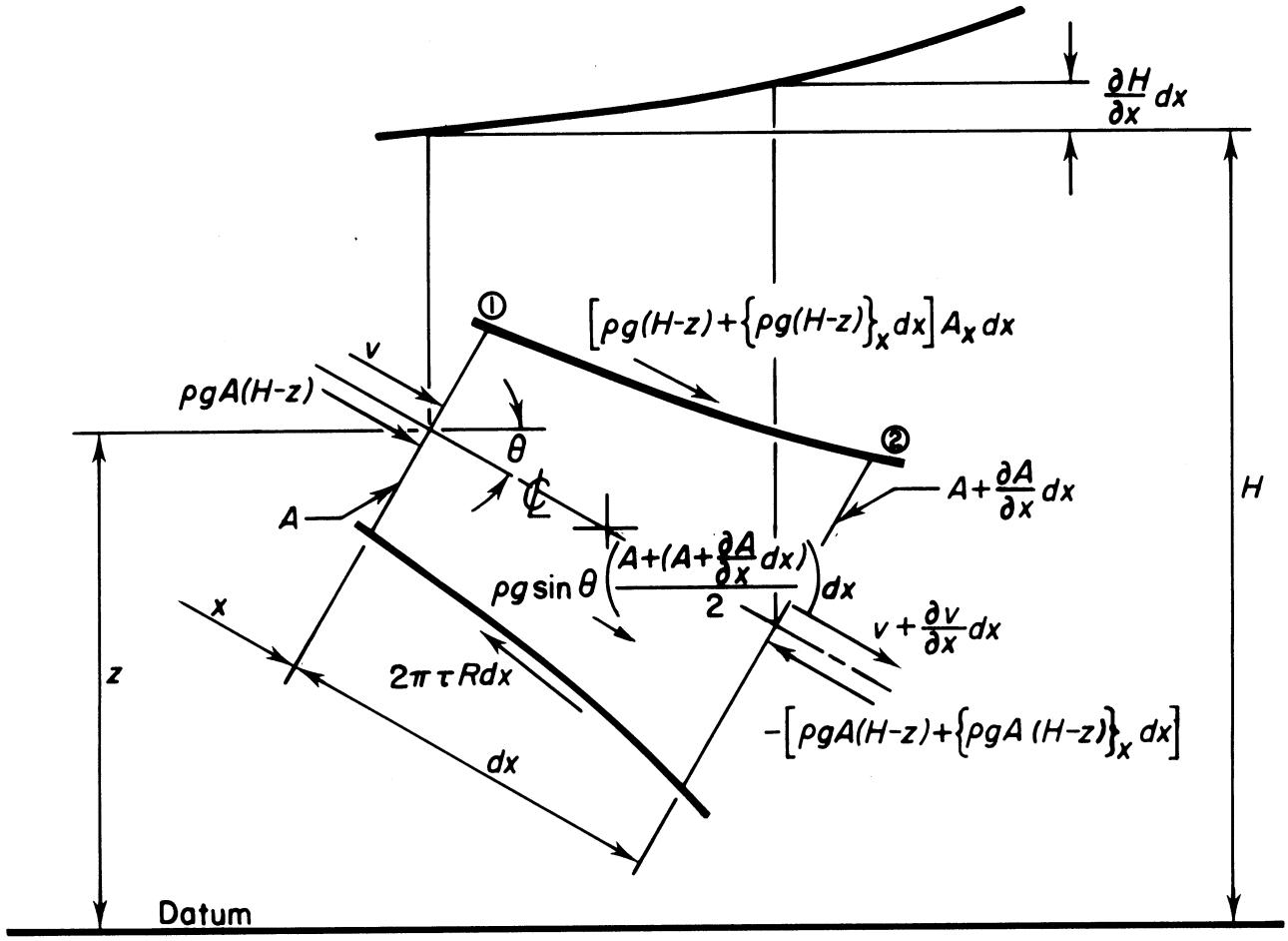

Figure 3. Definition Sketch Showing Transient Conditions in Pipe Segment Flowing Full.

$$\frac{\partial(\rho A dx)}{\partial t} \quad . \tag{2}$$

Equating the expressions given by Equation (1) and (2) according to the definition above, one has

$$- \frac{\partial(\rho A v)}{\partial x} dx = \frac{\partial(\rho A dx)}{\partial t} \tag{3}$$

Normally, x is independent of t and, therefore, $\frac{\partial(dx)}{\partial t}$ is zero. However, if the pipe is supported in such a manner that the pipe segment is subject to axial strain, η_x, then $\frac{\partial(dx)}{\partial t} = \frac{d\eta_x}{dt} dx$. In this expression η represents the strain; the subscript x, the direction. Consequently, expansion of Equation (3), subsequently divided by the mass of the fluid element, $\rho A dx$, results in the expression

$$v_x + v \frac{A_x}{A} + v \frac{\rho_x}{\rho} + \frac{A_t}{A} + \frac{\rho_t}{\rho} + \frac{d\eta_x}{dt} = 0 \tag{4}$$

or by rearranging

$$\frac{1}{\rho} (v\rho_x+\rho_t) + \frac{1}{A} (vA_x+A_t) + v_x + \frac{d\eta_x}{dt} = 0 \quad . \tag{5}$$

Here the subscripts x and t denote partial differentiation with the respective variable. However, since

$$\frac{d\rho}{dt} = \frac{\partial\rho}{\partial x} \frac{dx}{dt} + \frac{\partial\rho}{\partial t}$$

or simply

$$\frac{d\rho}{dt} = v\rho_x + \rho_t \ ,$$

and, similarly, because

$$\frac{dA}{dt} = vA_x + A_t \ ,$$

Equation (5) may be written

$$\frac{1}{\rho}\frac{d\rho}{dt} + \frac{1}{A}\frac{dA}{dt} + v_x + \frac{d\eta_x}{dt} = 0 \ . \tag{6}$$

The essential task, now, is to represent the liquid density and the pipe cross-sectional area changes with respect to time as functions of the velocity of the flow and the pressure. First, by recalling that the bulk modulus of elasticity for liquids denoted by K is defined as

$$K = - \frac{dp}{d\forall/\forall} = \frac{dp}{d\rho/\rho} \ , \tag{7}$$

where p is the pressure and $\forall$ is the volume, one can rewrite Equation (7) as

$$\frac{d\rho}{\rho} = \frac{dp}{K} \ . \tag{8}$$

Subsequent differentiation with respect to time gives

$$\frac{1}{\rho}\frac{d\rho}{dt} = \frac{1}{K}\frac{dp}{dt} \ . \tag{9}$$

In order to treat the change in the cross-sectional area of the pipe, consider the circumferential strain to be given by η_c. Therefore, the increase in the cross-sectional area with time is given by

$$\frac{dA}{dt} = \frac{d\eta_c}{dt}(2\pi R)R = \frac{d\eta_c}{dt} 2\pi R^2 = 2A\frac{d\eta_c}{dt}$$

or

$$\frac{1}{A}\frac{dA}{dt} = 2\frac{d\eta_c}{dt} \ . \tag{10}$$

Thus, Equation (6) becomes

$$\frac{1}{K}\frac{dp}{dt} + 2\frac{d\eta_c}{dt} + v_x + \frac{d\eta_x}{dt} = 0 \ . \tag{11}$$

The magnitudes of the various terms in the continuity equation clearly depend upon the radial or the circumferential strain. But the circumferential strain depends upon the physical characteristics of the pipe itself, as well as upon the restraint to deformation imposed by the particular manner in which it is supported. In order to evaluate the terms $d\eta_c/dt$ and $d\eta_x/dt$, a general expression must be developed in which the physical characteristics of the pipe and its support conditions are treated as parameters.

The relationship between stress and strain is commonly given by Stress/E = Strain, where E is the modulus of elasticity of the pipe wall material. Moreover, stresses in any one direction create strains in the two other normal directions according to Poisson's ratio, μ. Thus, the following relationships can be written to express the radial, circumferential, and axial pipe strains in terms of their appropriate stresses:

$$\eta_r = \frac{1}{E}\left[\sigma_r - \mu(\sigma_c + \sigma_x)\right] \tag{12}$$

$$\eta_c = \frac{1}{E}\left[\sigma_c - \mu(\sigma_r + \sigma_x)\right] \tag{13}$$

$$\eta_x = \frac{1}{E}\left[\sigma_x - \mu(\sigma_r + \sigma_c)\right] \tag{14}$$

The term, σ, denotes stress; the subscripts r, c, and x denote the principal directions. These relationships provide the connecting link which will subsequently allow Equation (11) to be rewritten in terms of velocities and pressures.[9,40,59]

Consider the stressed element located within the pipe wall shown in Figure 4. The element, which is denoted by abcdefgh, has the length, the curved-width, and the thickness dimensions, d_x, $rd\theta$, and dr,

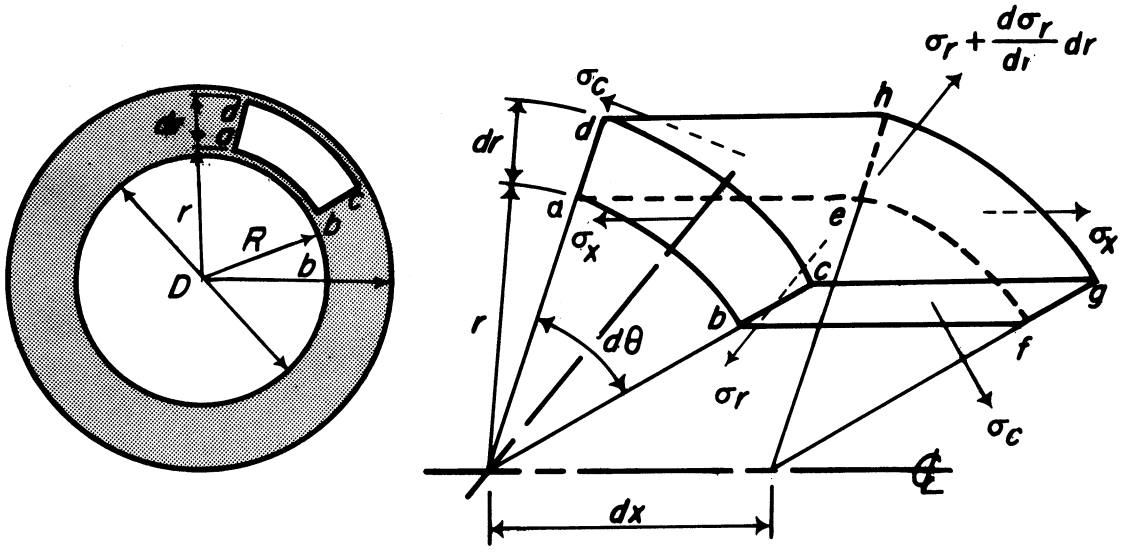

Figure 4. Definition Sketch Depicting Stressed Element Located Within Pipe Wall. Transverse Cross-Section is Shown on the Left and Three Dimensional Enlargement is Shown on the Right.

respectively. In Figure 4, $d\theta$ is the radial angle subtended by the element, r is the radial distance to the element measured from the axis of the pipe, R is the inside pipe radius, and b is the outside pipe radius.

When considering the open-ended element shown in Figure 4, one must be mindful of two basic conditions which are assumed valid:

(a) The axial strain created by the radial stress is constant.

(b) Displacement perpendicular to the axis is radial and dependent only upon the radius.

The unstrained radial distance to the particle is r. Let its strained radial distance be given by $r + \xi$ where ξ is the total increment of displacement in the radial direction. Thus, the radial strain is

$$\eta_r = \frac{d\xi}{dr} ,$$

while the circumferential strain is

$$\eta_c = \frac{\xi}{r} .$$

The axial strain is a constant,

$$\eta_x = \text{constant} .$$

The summation of forces acting upon the element $abcdefgh$, in which the outward direction of the radial bisector in Figure 4 is taken to be positive, is

$$\sigma_r r d\theta + \sigma_c dr \frac{d\theta}{2} + \sigma_c dr \frac{d\theta}{2} - (\sigma_r + \frac{d\sigma_r}{dr} dr)(r+dr)d\theta = 0$$

or

$$\sigma_r r d\theta + \sigma_c dr d\theta - \sigma_r r d\theta - \sigma_r dr d\theta - \frac{r d\sigma_r}{dr} dr d\theta - \frac{d\sigma_r}{dr} (dr)^2 d\theta = 0$$

or, after combining like terms, eliminating higher order terms, and dividing by $dr d\theta$

$$\sigma_c - \sigma_r - r \frac{d\sigma}{dr} = 0 .$$

Reduced to simplest terms

$$\sigma_c = \frac{d(r\sigma_r)}{dr} . \tag{15}$$

Equations (12-14) can be rewritten as follows:

$$\sigma_r - \mu(\sigma_c+\sigma_x) = \eta_r E = E \frac{d\xi}{dr} \tag{16}$$

$$\sigma_c - \mu(\sigma_r+\sigma_x) = \eta_c E = E \frac{\xi}{r} \tag{17}$$

$$\sigma_x - \mu(\sigma_r+\sigma_c) = \eta_x E = \text{constant} . \tag{18}$$

However, by rewriting Equation (17) as

$$r\{\sigma_c-\mu(\sigma_r+\sigma_x)\} = E\xi$$

and then differentiating with respect to r ,

$$\{\sigma_c-\mu(\sigma_r+\sigma_x)\} + \frac{d}{dr}\{\sigma_c-\mu(\sigma_r+\sigma_x)\} = E \frac{d\xi}{dr} , \tag{19}$$

one can eliminate $E \frac{d\xi}{dr}$ from Equation (16) and (19). This is now done. Let $\psi = \sigma_r r$ in Equation (16) and (19):

$$\frac{\psi}{r} - \mu\left(\frac{d\psi}{dr} + \sigma_x\right) = \frac{d}{dr}\left(r \frac{d\psi}{dr} - \mu r\sigma_x - \mu\psi\right)$$

$$\frac{\psi}{r} - \mu \frac{d\psi}{dr} - \mu\sigma_x = r \frac{d^2\psi}{dr^2} + \frac{d\psi}{dr} - \mu r \frac{d\sigma_x}{dr} - \mu\sigma_x - \mu \frac{d\psi}{dr}$$

$$r\frac{d^2\psi}{dr^2} + \frac{d\psi}{dr} - \frac{\psi}{r} = \mu r \frac{d\sigma_x}{dr} \quad . \tag{20}$$

Differentiation of Equation (18) with respect to r produces

$$\frac{d\sigma_x}{dr} - \mu \frac{d(\sigma_r+\sigma_c)}{dr} = 0$$

or, written in terms of ψ ,

$$\frac{d\sigma_x}{dr} = \mu \left(\frac{1}{r}\frac{d\psi}{dr} - \frac{\psi}{r^2} + \frac{d^2\psi}{dr^2} \right) \tag{21}$$

Therefore, using Equation (21) one may write

$$\mu r \frac{d\sigma_x}{dr} = \mu^2 \left(\frac{d\psi}{dr} - \frac{\psi}{r} + r\frac{d^2\psi}{dr^2} \right) ,$$

which when substituted into Equation (20) produces the homogeneous linear differential equation

$$\left(\frac{d^2\psi}{dr^2} + \frac{1}{r}\frac{d\psi}{dr} - \frac{\psi}{r^2} \right) (1-\mu^2)r = 0 \tag{22}$$

By letting $\psi = r\varphi$ for which $\psi' = r\varphi' + \varphi$ and $\psi'' = r\varphi'' + 2\varphi'$, Equation (22) may be solved in the following manner:

$$r\varphi'' + 2\varphi' + \varphi' + \frac{\varphi}{r} - \frac{\varphi}{r} = 0$$

$$\varphi'' + \frac{3}{r}\varphi' = 0 \quad .$$

The integration factor for this equation is $\exp[\int \frac{3}{r}\, dr] = \exp^{(3 \ln r)} = e^{\ln r^3} = r^3$, thus

$$r^3\varphi'' + 3r^2\varphi' = 0 \tag{23}$$

for which the exact differential is $r^3\varphi'$. In order for Equation (23) to be valid $r^3\varphi'$ must equal a constant. Thus,

$$\varphi' = \frac{C_1}{r^3}$$

and

$$\varphi = \int \varphi' dr = -\frac{C_1}{2r^2} + C_3 = \frac{C_2}{r^2} + C_3 .$$

But because $\varphi = \frac{\psi}{r}$, it is possible to write

$$\psi = \frac{C_2}{r} + rC_3$$

and since $\sigma_r = \frac{\psi}{r}$,

$$\sigma_r = C_3 + \frac{C_2}{r^2} , \tag{24}$$

and from Equation (15)

$$\sigma_c = \frac{d(r\sigma_r)}{dr} = C_3 - \frac{C_2}{r^2} . \tag{25}$$

Once the constants C_3 and C_2 are evaluated, the circumferential and radial stress terms will become known.

Let $\sigma_r = -p$ when the internal pipe pressure is p and the inner radius is R. By the same token let $\sigma_r = -q$ when the pressure acting upon the pipe externally is q and the outer pipe radius is b. Then one can write

$$p - q = \frac{C_2}{b^2} - \frac{C_2}{R^2} = C_2 \left(\frac{R^2 - b^2}{R^2 b^2} \right)$$

or

$$C_2 = \frac{(p-q)R^2 b^2}{R^2 - b^2} . \tag{26}$$

Consequently, evaluation of C_3 is readily accomplished using Equation (24).

$$-p = C_3 + \frac{(p-q)R^2b^2}{(R^2-b^2)R^2}$$

or

$$C_3 = -\left(\frac{pR^2-pb^2+pb^2-qb^2}{R^2-b^2}\right) = \frac{qb^2-pR^2}{R^2-b^2} \quad . \tag{27}$$

Thus, the radial and circumferential stress relationships may be written

$$\sigma_r = \frac{1}{b^2-R^2}\left[pR^2 - qb^2 + \frac{R^2b^2}{r^2}(q-p)\right] \tag{28}$$

$$\sigma_c = \frac{1}{b^2-R^2}\left[pR^2 - qb^2 - \frac{R^2b^2}{r^2}(q-p)\right] . \tag{29}$$

Note, also, that the combined stress term,

$$\sigma_r + \sigma_c = 2\,\frac{(pR^2-qb^2)}{b^2-R^2} ,$$

is independent of both the circumferential and the axial positions; thus, σ_x is truly a constant at any cross section as originally postulated.

Clearly, there are several methods by which a section of pipe may be supported. But it should be just as apparent that the tolerable, pressure-induced strains are governed in large measure by the support conditions. Using Equation (12) and (14), one can write the relationship given in Equation (11) in terms of the appropriate stress conditions:

$$\frac{1}{K}\frac{dp}{dt} + \frac{2}{E}\left[\frac{d\sigma_c}{dt} - \mu\left(\frac{d\sigma_r}{dt} + \frac{d\sigma_x}{dt}\right)\right] + v_x + \frac{1}{E}\left[\frac{d\sigma_x}{dt} - \mu\left(\frac{d\sigma_r}{dt} + \frac{d\sigma_c}{dt}\right)\right] = 0 \tag{30}$$

Let the external pipe pressure, q, be considered zero. Equation (30) may then be evaluated for the three commonly encountered conditions of pipe support described below:

Condition I. Assume a section of pipe anchored at one end, but otherwise free to deform both radially and axially with respect

to this fixed location. In order to determine the deformation which occurs within the pipe let $r = R$. Then, from Equations (29) and (28), respectively, it is apparent that

$$\sigma_c = \frac{pR^2}{b^2-R^2}\left[1 + \frac{b^2}{R^2}\right] \tag{31}$$

while

$$\sigma_r = \frac{pR^2}{b^2-R^2}\left[1 - \frac{b^2}{R^2}\right] . \tag{32}$$

The axial stress, which is determined by dividing the end pressure force by the cross sectional pipe area, is given by

$$\sigma_x = \frac{p\pi R^2}{\pi(b^2-R^2)} = \frac{pR^2}{(b^2-R^2)} . \tag{33}$$

Therefore, Equation (30) can be written

$$\frac{1}{K}\frac{dp}{dt} + \frac{2}{E}\left[\frac{dp}{dt}\left(\frac{R^2}{b^2-R^2}\right)\left(1 + \frac{b^2}{R^2}\right) - \mu\,\frac{dp}{dt}\left(\frac{R^2}{b^2-R^2}\right)\left(1 - \frac{b^2}{R^2} + 1\right)\right]$$

$$+ v_x + \frac{1}{E}\left[\frac{dp}{dt}\left(\frac{R^2}{b^2-R^2}\right) - \mu\,\frac{dp}{dt}\left(\frac{R^2}{b^2-R^2}\right)\left(1 - \frac{b^2}{R^2} + 1 + \frac{b^2}{R^2}\right)\right] = 0$$

or

$$\frac{dp}{dt}\left[\frac{1}{K} + \frac{1}{E}\left(\frac{R^2}{b^2-R^2}\right)\left\{3 + \frac{2b^2}{R^2} - \mu\left(6 - \frac{2b^2}{R^2}\right)\right\}\right] + v_x = 0$$

or simply

$$\frac{dp}{dt}\left[\frac{1}{K} + \frac{1}{E}\left(\frac{R}{b-R}\right)c_1\right] + v_x = 0 \tag{34}$$

where $c_1 = \frac{2R}{b+R}\left(1.5 - 3\mu + \frac{b^2}{R^2}(1+\mu)\right)$. (35)

Note that differentiation of R and b with respect to time t results in insignificant terms which are not included above.

Condition II. Assume a section of pipe anchored throughout its length such that axial strains cannot occur, but otherwise free to undergo radial deformation. In order to determine the internal deformation within the pipe let $r = R$. Then, Equations (29) and (28) give

$$\sigma_c = \frac{pR^2}{b^2-R^2}\left[1 + \frac{b^2}{R^2}\right] \tag{36}$$

and

$$\sigma_r = \frac{pR^2}{b^2-R^2}\left[1 - \frac{b^2}{R^2}\right] \tag{37}$$

Because no strain is permitted in the axial direction, the axial stress must be

$$\sigma_x = 2\mu p \frac{R^2}{b^2-R^2} \tag{38}$$

according to Poisson's ratio. In this instance Equation (30) becomes

$$\frac{1}{K}\frac{dp}{dt} + \frac{2}{E}\left[\frac{dp}{dt}\left(\frac{R^2}{b^2-R^2}\right)\left(1 + \frac{b^2}{R^2}\right) - \mu\,\frac{dp}{dt}\left(\frac{R^2}{b^2-R^2}\right)\left(1 - \frac{b^2}{R^2} + 2\mu\right)\right] + v_x = 0$$

or

$$\frac{dp}{dt}\left[\frac{1}{K} + \frac{2}{E}\left(\frac{R^2}{b^2-R^2}\right)\left(1 + \frac{b^2}{R^2} - \mu + \mu\,\frac{b^2}{R^2} - 2\mu^2\right)\right] + v_x = 0$$

or simply

$$\frac{dp}{dt}\left[\frac{1}{K} + \frac{1}{E}\left(\frac{R}{b-R}\right)c_2\right] + v_x = 0 \tag{39}$$

where $$c_2 = \frac{2R}{b+R}\left(1 - \mu - 2\mu^2 + \frac{b^2}{R^2}(1+\mu)\right) . \tag{40}$$

Condition III. Assume a section of pipe with numerous expansion joints or their equivalent, such that radial deformation may occur without the occurrence of axial stresses or strains. Let $r = R$ in order that the inner deformation may be found. Then, Equations(29) and (28) give

$$\sigma_c = \frac{pR^2}{b^2-R^2}\left[1 + \frac{b^2}{R^2}\right] \tag{41}$$

and

$$\sigma_r = \frac{pR^2}{b^2-R^2}\left[1 - \frac{b^2}{R^2}\right] \tag{42}$$

From the conditions stated

$$\sigma_x = 0 \tag{43}$$

and Equation (30) becomes

$$\frac{1}{K}\frac{dp}{dt} + \frac{2}{E}\left[\frac{dp}{dt}\left(\frac{R^2}{b^2-R^2}\right)\left(1 + \frac{b^2}{R^2}\right) - \mu\,\frac{dp}{dt}\left(\frac{R^2}{b^2-R^2}\right)\left(1 - \frac{b^2}{R^2}\right)\right] + v_x = 0 \tag{44}$$

or

$$\frac{dp}{dt}\left[\frac{1}{K} + \frac{2}{E}\left(\frac{R^2}{b^2-R^2}\right)\left(1 + \frac{b^2}{R^2} - \mu + \mu\,\frac{b^2}{R^2}\right)\right] + v_x = 0$$

or simply

$$\frac{dp}{dt}\left[\frac{1}{K} + \frac{1}{E}\left(\frac{R}{b-R}\right) c_3\right] + v_x = 0 \tag{45}$$

where

$$c_3 = \frac{2R}{b+R}\left(1 - \mu + \frac{b^2}{R^2}(1+\mu)\right) . \tag{46}$$

Thus, to summarize, the continuity equation may be written

$$\frac{dp}{dt}\left[\frac{1}{K} + \frac{c}{E}\frac{R}{(b-R)}\right] + v_x = 0 \qquad (47)$$

for which the parameter, c, in the three particular mounting conditions investigated above is given by the following:

$$c_1 = \frac{2R}{b+R}\left[1.5 - 3\mu + \frac{b^2}{R^2}(1+\mu)\right] \qquad (35)$$

$$c_2 = \frac{2R}{b+R}\left[1 - \mu - 2\mu^2 + \frac{b^2}{R^2}(1+\mu)\right] \qquad (40)$$

$$c_3 = \frac{2R}{b+R}\left[1 - \mu + \frac{b^2}{R^2}(1+\mu)\right] . \qquad (46)$$

Halliwell,[24] following a different procedure, derived the same results at approximately the same time. For the limiting condition when $b \to R$ and the pipe wall becomes thin, the three parameters reduce to simply the following:

$$c_1 = 2\left[\frac{5}{4} - \mu\right] \qquad (48)$$

$$c_2 = 2\left[1 - \mu^2\right] \qquad (49)$$

$$c_3 = 2 . \qquad (50)$$

The variation of the coefficient, c, is shown as a function of the ratio of the outside to inside pipe radii for various commonly encountered values of Poisson's ratio in Figure 5. Each of the three conditions of support is considered.

By referring back to Figure 3 it is apparent that the pressure acting at cross section (1) is given in terms of the static head

$$p = \rho g(H-z)$$

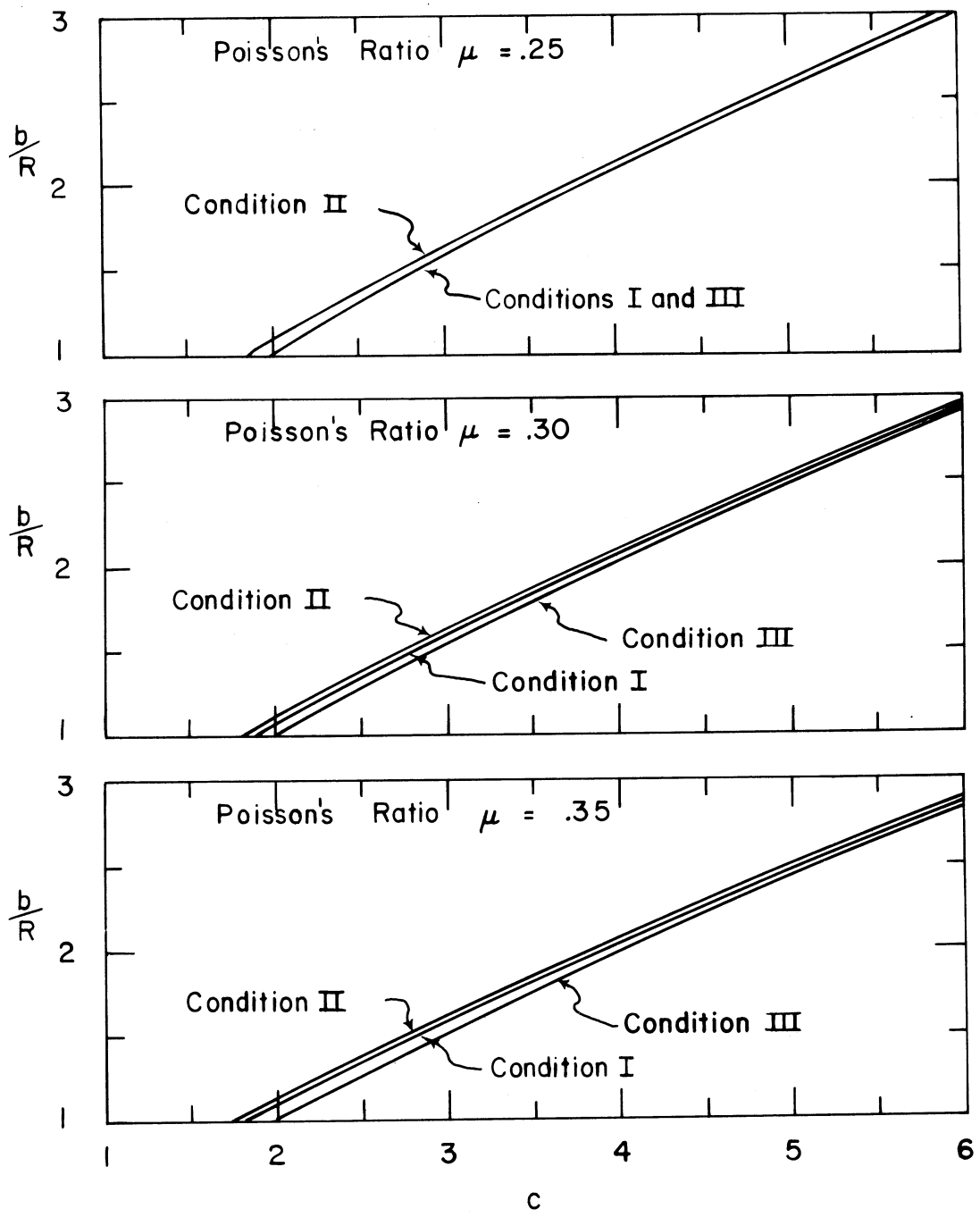

Figure 5. Curves Defining Relationship Between Pipe Constraint Coefficient, c , and the Ratio of Outside to Inside Pipe Radii, b/R , for Various Conditions of Constraint and Different Values of Poisson's Ratio.

Since $$\frac{dp}{dt} = \frac{\partial p}{\partial x}\frac{dx}{dt} + \frac{\partial p}{\partial t} = \frac{\partial p}{\partial x} v + \frac{\partial p}{\partial t} \tag{51}$$

it is possible to determine $\frac{\partial p}{\partial x}$ and $\frac{\partial p}{\partial t}$, as follows:

$$\frac{\partial p}{\partial x} = \rho g(H_x - z_x) + g(H-z)\rho_x \tag{52}$$

$$\frac{\partial p}{\partial t} = \rho g(H_t - 0) + g(H-z)\rho_t \tag{53}$$

However, $\frac{\partial z}{\partial x} = -\sin\theta$; Equation (52) thus becomes

$$\frac{\partial p}{\partial x} = \rho g(H_x + \sin\theta) + g(H-z)\rho_x \tag{54}$$

Integration of Equation (8) results in

$$p = K \ln \rho + c'$$

Subsequent partial differentiation of p with respect to x and t gives

$$p_x = K \frac{\rho x}{\rho}$$

and

$$p_t = K \frac{\rho t}{\rho}$$

Thus, one may write

$$\frac{1}{K} p_x = \frac{\rho x}{\rho} = \frac{\rho g}{K} (H_x + \sin\theta) + \frac{g}{K} (H-z)\rho_x$$

and

$$\frac{1}{K} p_t = \frac{\rho t}{\rho} = \frac{\rho g}{K} (H_t) + \frac{g}{K} (H-z)\rho_t$$

or, after gathering like terms

$$\rho_x = \rho^2 g(H_x + \sin\theta)\left(\frac{1}{K - \rho g(H-z)}\right) \tag{55}$$

and

$$\rho_t = \rho^2 g\, H_t\left(\frac{1}{K-\rho g(H-z)}\right) \tag{56}$$

Equations(55) and (56) may be substituted into Equations(53) and (54) and after gathering like terms;

$$\frac{\partial p}{\partial t} = \rho g\, H_t\left[1 + \rho g\, \frac{(H-z)}{(K-\rho g(H-z))}\right]$$

and

$$\frac{\partial p}{\partial x} = \rho g(H_x+\sin\theta)\left[1 + \rho g\, \frac{(H-z)}{(K-\rho g(H-z))}\right]$$

Thus, using the above expressions for $\frac{\partial p}{\partial x}$ and $\frac{\partial p}{\partial t}$, one may rewrite Equation (51) as

$$\frac{dp}{dt} = \rho g\left[(H_x+\sin\theta)v + H_t\right]\left[1 + \rho g\, \frac{(H-z)}{(K-\rho g(H-z))}\right] . \tag{57}$$

Consequently, the continuity equation, Equation (47), may be written

$$\rho g\left[(H_x+\sin\theta)v + H_t\right]\left[\frac{1}{K} + \frac{C}{E}\,\frac{R}{(b-R)}\right]\left[1 + \rho g\, \frac{(H-z)}{K-\rho g(H-z)}\right] + v_x = 0$$

or simply

$$H_t + v(H_x+\sin\theta) = -\frac{a^2}{g}\, v_x\, \Phi \tag{58}$$

where

$$a = \sqrt{\frac{1}{\rho\left(\frac{1}{K} + \frac{C}{E}\left(\frac{R}{b-R}\right)\right)}} \tag{50}$$

and

$$\Phi = \left[\frac{1}{1 + \frac{\rho g(H-z)}{K-\rho g(H-z)}}\right] \tag{60}$$

The term a is an expression for the celerity of the pressure pulse through the pipe system when flowing full; the term Φ compensates for the change in the bulk modulus of elasticity with increasing pressure. For water the term Φ remains approximately unity for moderate pressures. For the range of pressure heads encountered in this study the magnitude of Φ will be assumed to be unity.

Equation of Motion

According to Newton's second law of motion, the net flux of momentum from the control segment and the time rate of change of momentum within the segment must be instantaneously equivalent to the resultant of the external forces acting on the segment.

Consider again the control segment of a circular pipe flowing full shown in Figure 3. Recall that the area at cross section (1) is A and the area at cross section (2) is $A + \frac{\partial A}{\partial x} dx$. The gradient of the pipe is downward (negative gradient) at an angle θ. Flow occurs in the positive x-direction.

The mass of the element is given by

$$\rho(A + \frac{1}{2} \frac{\partial A}{\partial x} dx)\, dx \ .$$

The acceleration in the positive x-direction is given by the total derivative of the velocity with respect to time

$$\frac{dv}{dt} = \frac{\partial v}{\partial x} \frac{dx}{dt} + \frac{\partial v}{\partial t} = v \frac{\partial v}{\partial x} + \frac{\partial v}{\partial t} \ .$$

The product of the mass and the acceleration is

$$\rho A v \frac{\partial v}{\partial x} dx + \rho A \frac{\partial v}{\partial t} dx + \frac{1}{2} \rho v \frac{\partial A}{\partial x} \frac{\partial v}{\partial x} (dx)^2 + \frac{1}{2} \rho \frac{\partial A}{\partial x} \frac{\partial v}{\partial t} (dx)^2$$

or, after eliminating higher order terms, simply

$$\rho A v v_x dx + \rho A v_t dx \tag{61}$$

The pressure force acting upon the cross section at (1) is

$$\rho g A(H-z) \ . \tag{62}$$

At cross section (2) the pressure force is

$$-\left[\rho g A(H-z) + (\rho g A(H-z))_x dx\right] \ . \tag{63}$$

An additional pressure force acting upon the expanding cross section of the pipe between (1) and (2) is

$$\left[\rho g(H-z) + (\rho g(H-z))_x dx\right] A_x dx \ . \tag{64}$$

Fluid resistance to motion is interpreted as a boundary shear force and denoted by

$$-\tau 2\pi R dx \ , \tag{65}$$

where τ is the fluid shear stress at the pipe wall. The body force due to gravity is

$$\rho g \sin\theta \left[\frac{A + (A + \frac{\partial A}{\partial x} dx)}{2}\right] dx \tag{66}$$

The summation of Equations (62) through (66) is the resultant of the forces acting upon the control segment in the x-direction:

$$\begin{aligned} &\rho g A(H-z) - \rho g A(H-z) - \rho g A(H)_x dx - \rho g A \sin\theta dx \\ &\quad - \rho g(H-z) A_x dx + \rho g(H-z) A_x d_x + \rho g(H_x + \sin\theta) A_x (dx)^2 \\ &\quad - \tau 2\pi R dx + \rho g \sin\theta A dx + \rho g \frac{\sin\theta}{2} \frac{\partial A}{\partial x} (dx)^2 \end{aligned}$$

or upon the elimination of higher order terms

$$- \rho g A H_x dx - 2\tau\pi R dx \quad . \tag{67}$$

The equation of motion may now be written by equating Equations(61) and (67),

$$- \rho g A H_x dx - 2\tau\pi R dx = \rho A v v_x dx + \rho A v_t dx \tag{68}$$

Now then, for dynamic equilibrium of the flow in the pipe, the stress-created shear force at the pipe wall must equal the so-called frictional head loss per unit length, L , that is

$$\tau 2\pi R = \frac{\Delta p}{\Delta L} \pi R^2 = \rho g \frac{\Delta H_f}{\Delta L} \pi R^2$$

where H_f is the friction loss in terms of head loss. The Darcy-Weisbach expression for head loss per unit length resulting from friction is

$$\frac{\Delta H_f}{\Delta L} = \frac{f}{2R} \frac{v|v|}{2g} \quad .$$

Consequently, the shear stress is

$$\tau = \rho f \frac{v|v|}{8}$$

Therefore, substituting Equation (69) into Equation (68) and dividing by $\rho g A dx$ results in the relationship

$$H_x + \frac{fv|v|}{2gD} \quad \frac{1}{g} (v\, v_x + v_t) = 0 \cdot \tag{70}$$

The absolute value sign is introduced into the frictional term so that it has the proper sign depending on the direction of flow.

Characteristics Equations

The partial differential expressions, Equations(58) and (70), derived in the previous section and representing transient liquid motion in a pipe flowing full, may now be rewritten as

$$\Gamma_1 = v_t + v\,v_x + gH_x + \frac{fv|v|}{2D} = 0 \qquad (71)$$

$$\Gamma_2 = \frac{a^2}{g} v_x + H_t + vH_x + v\sin\theta = 0 \,. \qquad (72)$$

These two equations form a set of simultaneous, quasi-linear, hyperbolic, partial differential equations of the first order in two independent and two dependent variables. Again the subscripts x and t indicate partial differentiation with respect to these independent variables.

The expressions Γ_1 and Γ_2 may be combined linearly such that

$$\Omega = \Gamma_1 + n\Gamma_2 \qquad (73)$$

or

$$\Omega = v_t + \left(v + \frac{na^2}{g}\right) v_x + nH_t + (g+nv)H_x + \frac{f}{2D} v|v| + nv\sin\theta = 0 \qquad (74)$$

Now, if $v = v(x,t)$ and $H = H(x,t)$ are solutions of Equations(71) and (72), then

$$dv = \frac{\partial v}{\partial x} dx + \frac{\partial v}{\partial t} \quad \text{and} \quad dH = \frac{\partial H}{\partial x} dx + \frac{\partial H}{\partial t}$$

or

$$\frac{dv}{dt} = v_t + v_x \frac{dx}{dt} \quad \text{and} \quad \frac{dH}{dt} = H_t + H_x \frac{dx}{dt} \,. \qquad (75)$$

From inspection of Equation 74 it is readily apparent that it may be rewritten

$$\Omega = \frac{dv}{dt} + n\frac{dH}{dt} + \frac{f}{2D}v|v| + nv\sin\theta = 0 \tag{76}$$

provided

$$\frac{dx}{dt} = v + \frac{na^2}{g} = \frac{g+nv}{n} \tag{77}$$

or in other words provided

$$\frac{dv}{dt} = v_t + (v + \frac{na^2}{g})\, v_x$$

and

$$\frac{dH}{dt} = H_t + (\frac{g}{n} + v)\, H_x \,.$$

From Equation (77) one finds

$$n^2a^2 = g^2$$

or

$$n = \pm\frac{g}{a} \tag{78}$$

By substituting Equation (78) into Equations(76) and (77), one has the pair of relations

$$C_+\begin{cases}\Omega dt = dv + \frac{g}{a}dH + \frac{f}{2D}v|v|dt + \frac{g}{a}v\sin\theta dt = 0 & (79)\\ \frac{dt}{dx} = \frac{1}{v+a} & (80)\end{cases}$$

and

$$C_-\begin{cases}\Omega dt = dv - \frac{g}{a}dH + \frac{f}{2D}v|v|dt - \frac{g}{a}v\sin\theta dt = 0 & (81)\\ \frac{dt}{dx} = \frac{1}{v-a} & (82)\end{cases}$$

To summarize what has been accomplished, Equations(79) and (81) are two separate total differential equations for which solutions for v and H may be determined along the families of characteristics curves occurring in the x-t plane. These curves are defined by the total differential expressions given by Equations(80) and (82), respectively. In other words, the characteristics curves represent the paths along which infinitesimally small velocity and pressurehead differences propagate. Equations (79) and (80) are applicable along a positively directed characteristics curve, while Equations(81) and (82) are applicable along the negatively-directed characteristics.

Finite Difference Solution

Equations (79-82) may now be solved by means of a finite difference technique. If the step size of the increments used in the solution is small, one can solve by a first order approximation for which

$$\int_{x_o}^{x_1} f(x)dx \approx f(x_o)(x_1-x_o) \quad ;$$

otherwise, a second order approximation technique requiring iteration should be considered. A first order technique is used throughout this development.

Consider the fact that for a set of two hyperbolic differential equations the characteristics curves at a point have real and distinct directions; therefore, the curves must intersect at the point. Let P_i be a point on the x-t plane as shown in Figure 6. Two characteristics curves from the families of positively and negatively directed characteristics curves are shown passing through P_i .

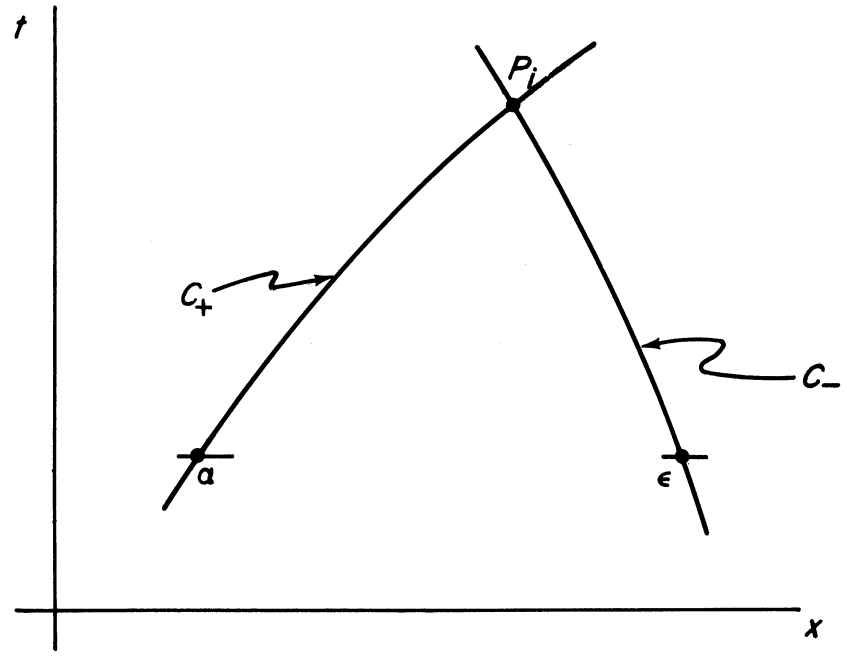

Figure 6. Definition Sketch Showing Intersection of C+ and C- Characteristics Curves in the x-t Plane.

The objective of this solution technique is to provide a means for obtaining values of velocity and head (pressure) at selected locations throughout the x-t plane. Figure 7 shows a portion of a rectangular grid in the x-t plane. The two pairs of characteristics equations, Equations (79-82), representing transient motion in a pipe flowing full may be written in the following manner:

$$\left.\begin{aligned} dt - \frac{dx}{v+a} &= 0 \\ dv + \frac{g}{a}\,dH + \left(\frac{f}{2D}\,v|v| + \frac{g}{a}\,v\sin\theta\right)\,dt &= 0 \end{aligned}\right\} C_+$$

$$\left.\begin{aligned} dt - \frac{dx}{v-a} &= 0 \\ dv - \frac{g}{a}\,dH + \left(\frac{f}{2D}\,v|v| - \frac{g}{a}\,v\sin\theta\right)\,dt &= 0 \end{aligned}\right\} C_-$$

When written in incremental form these equations become

$$(t_P - t_\alpha) - \frac{1}{(v+a)_\alpha}\,(x_P - x_\alpha) = 0 \qquad (83)$$

$$(v_P - v_\alpha) + (H_P - H_\alpha)\,\frac{g}{a_\alpha} + \left(\frac{f}{2D}\,v|v| + \frac{g}{a}\,v\sin\theta\right)_\alpha (t_P - t_\alpha) = 0 \qquad (84)$$

$$(t_P - t_\epsilon) - \frac{1}{(v-a)_\epsilon}\,(x_P - x_\epsilon) = 0 \qquad (85)$$

$$(v_P - v_\epsilon) - (H_P - H_\epsilon)\,\frac{g}{a_\epsilon} + \left(\frac{f}{2D}\,v|v| - \frac{g}{a}\,v\sin\theta\right)_\epsilon (t_P - t_\epsilon) = 0 \qquad (86)$$

where the subscripts P, α, and ϵ refer to locations on the x-t plane in Figure 7. The grid in this figure has specified incremental distance and time intervals, Δx and Δt. The points P_o and P_n are boundary points. Note that time $t_L = t_\alpha = t_M = t_\epsilon = t_R$; also, note that distance $x_P = x_M$.

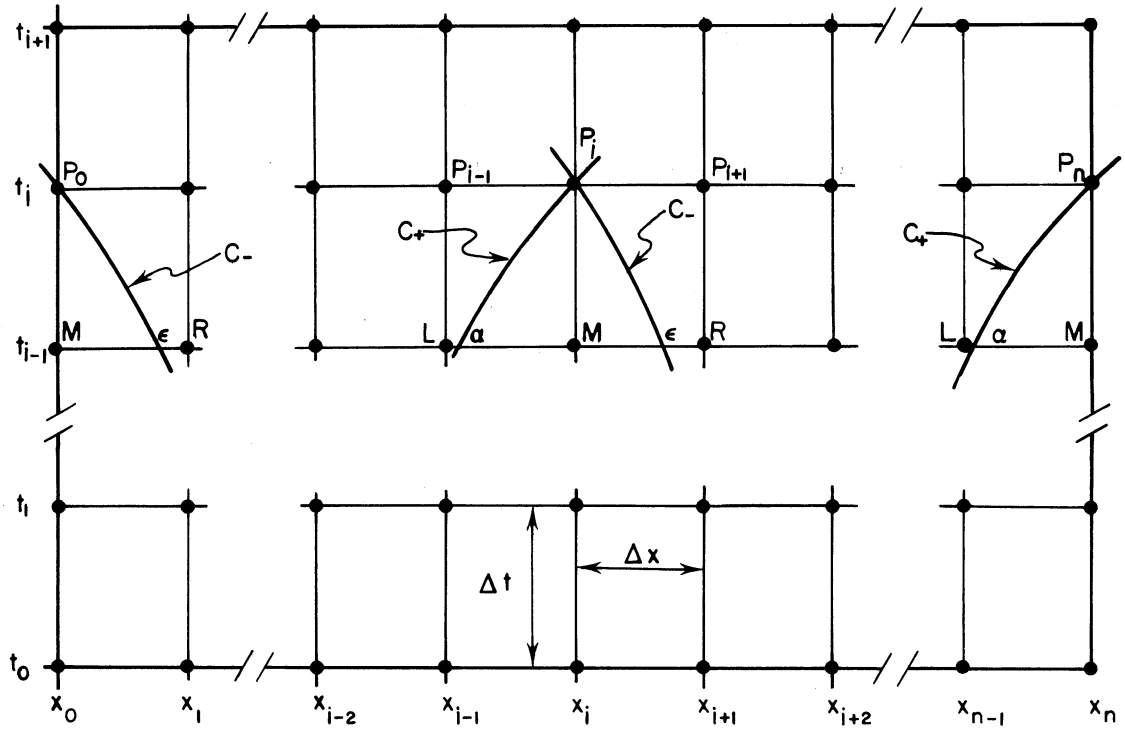

Figure 7. Definition Sketch Showing a Space-Time Grid Superimposed on the x-t Plane. Positive and Negative Characteristics Curves are Shown Passing Through Grid Intersection Points, P_0 , P_i , and P_n .

Clearly, the exact location of P_i which is at a grid point is known with respect to x and t. However, the locations of α and ϵ although known with respect to t, are unknown with respect to x and need to be so determined. The values of v and H at the points α and ϵ need to be determined in order to determine v_P and H_P. It is assumed that v and H are known at specific point (L,M,R, etc.) along the x-axis at the preceding times t_{i-1}, t_{i-2}, etc., either by having been initially given or previously calculated.

Linear interpolation is used to determine v and H at α and ϵ, thus

$$\frac{v_\alpha - v_L}{x_\alpha - x_L} = \frac{v_M - v_L}{x_M - x_L} = \frac{v_M - v_L}{\Delta x} \tag{87}$$

and

$$\frac{v_R - v_\epsilon}{x_R - x_\epsilon} = \frac{v_R - v_M}{x_R - x_M} = \frac{v_R - v_M}{\Delta x} \tag{88}$$

In order to determine v_α, v_ϵ, H_α, and H_ϵ one must note, first of all, that the two characteristics equations, namely, Equations (83) and (85), can be written

$$x_M - x_\alpha = (v+a)_\alpha \Delta t \tag{89}$$

and

$$x_\epsilon - x_M = -(v-a)_\epsilon \Delta t \tag{90}$$

These equations describe C_+ and C_-, respectively, at α and ϵ. Equations (87) and (88) may be respectively rewritten as

$$\left(\frac{v_\alpha - v_L}{v_M - v_L}\right) \Delta x = x_\alpha - x_L \tag{91}$$

and

$$\left(\frac{v_R - v_\epsilon}{v_R - v_M}\right) \Delta x = x_R - x_\epsilon \tag{92}$$

Inspection of Figure 7 clearly reveals

$$x_\alpha - x_L = \Delta x - (x_M - x_\alpha)$$

or, following substitution of Equation (89),

$$x_\alpha - x_L = \Delta x - (v+a)_\alpha \Delta t$$

into which substitution of Equation (91) yields

$$\left(\frac{v_\alpha - v_L}{v_M - v_L}\right) \Delta x = \Delta x - (v+a)_\alpha \Delta t$$

$$v_\alpha = v_L + (v_M - v_L)\left[1 - (v+a)_\alpha \frac{\Delta t}{\Delta x}\right] ,$$

or by approximation

$$v_\alpha = v_L + (v_M - v_L)\left[1 - (v+a)_M \frac{\Delta t}{\Delta x}\right] . \tag{93}$$

Figure 7 also reveals that

$$x_R - x_\epsilon = \Delta x - (x_\epsilon - x_M)$$

or, by substituting Equation (90),

$$x_R - x_\epsilon = \Delta x + (v-a)_\epsilon \Delta t ,$$

into which substitution of Equation (92) yields

$$v_\epsilon = v_R + (v_M - v_R)\left[1 + (v-a)_M \frac{\Delta t}{\Delta x}\right] . \tag{94}$$

The linear interpolation expressions used to determine H_α and H_ϵ are

$$\frac{H_\alpha - H_L}{x_\alpha - x_L} = \frac{H_M - H_L}{x_M - x_L} = \frac{H_M - H_L}{\Delta x}$$

and

$$\frac{H_R - H_\epsilon}{x_R - x_\epsilon} \quad \frac{H_R - H_M}{x_R - x_M} \quad \frac{H_R - H_M}{\Delta x} \quad .$$

The same general procedure used to determine v_α and v_ϵ is followed to determine H_α and H_ϵ, with the result that

$$H_\alpha = H_L + (H_M - H_L)\left[1 - (v+a)_M \frac{\Delta t}{\Delta x}\right] \tag{95}$$

and

$$H_\epsilon = H_R + (H_M - H_R)\left[1 + (v-a)_M \frac{\Delta t}{\Delta x}\right] \tag{96}$$

In summary, Equations (93)-(96), which define v_α, v_ϵ, H_α, and H_ϵ may be simply written

$$v_\alpha = v_M - (v_M - v_L)(v+a)_M \frac{\Delta t}{\Delta x} \tag{97}$$

$$H_\alpha = H_M - (H_M - H_L)(v+a)_M \frac{\Delta t}{\Delta x} \tag{98}$$

$$v_\epsilon = v_M + (v_M - v_R)(v-a)_M \frac{\Delta t}{\Delta x} \tag{99}$$

$$H_\epsilon = H_M + (H_M - H_R)(v-a)_M \frac{\Delta t}{\Delta x} \tag{100}$$

Note that $(v+a)_\alpha \approx (v+a)_M$ and $(v-a)_\epsilon \approx (v-a)_M$ are assumed to be entirely valid approximations provided the grid of points is closely spaced. Using the four equations for v_α, H_α, v_ϵ, and H_ϵ, one can rewrite Equations (84) and (86) in preparation for determining v_P and H_P :

$$(v_P-v_\alpha) + (H_P-H_\alpha)\left(\frac{g}{a}\right)_M + \left(\frac{f}{2D}\, v_\alpha|v_\alpha|\right)\Delta t + \left(\frac{g}{a}\right)_M v_\alpha \sin\theta\Delta t = 0 \quad (101)$$

$$(v_P-v_\epsilon) - (H_P-H_\epsilon)\left(\frac{g}{a}\right)_M + \left(\frac{f}{2D}\, v_\epsilon|v_\epsilon|\right)\Delta t - \left(\frac{g}{a}\right)_M v_\epsilon \sin\theta\Delta t = 0 \quad (102)$$

To solve for v_P and H_P, Equations(101) and (102) are first added,

$$2v_P - (v_\alpha+v_\epsilon) - (H_\alpha-H_\epsilon)\left(\frac{g}{a}\right)_M + \left(\frac{f}{2D}\right)_M (v_\alpha|v_\alpha|+v_\epsilon|v_\epsilon|)\Delta t + \left(\frac{g}{a}\right)_M (v_\alpha-v_\epsilon)\sin\theta\Delta t = 0$$

$$v_P = \tfrac{1}{2}(v_\alpha+v_\epsilon) + \tfrac{1}{2}(H_\alpha-H_\epsilon)\left(\frac{g}{a}\right)_M - \left(\frac{f}{4D}\right)_M (v_\alpha|v_\alpha|+v_\epsilon|v_\epsilon|)\Delta t - \tfrac{1}{2}\left(\frac{g}{a}\right)_M (v_\alpha-v_\epsilon)\sin\theta\Delta t \quad (103)$$

and then subtracted,

$$-v_\alpha + v_\epsilon + 2H_P\left(\frac{g}{a}\right)_M - (H_\alpha+H_\epsilon)\left(\frac{g}{a}\right)_M + \left(\frac{f}{2D}\right)_M (v_\alpha|v_\alpha|-v_\epsilon|v_\epsilon|)\Delta t + \left(\frac{g}{a}\right)_M (v_\alpha+v_\epsilon)\sin\theta\Delta t = 0$$

$$H_P = \tfrac{1}{2}(v_\alpha-v_\epsilon)\left(\frac{a}{g}\right)_M + \tfrac{1}{2}(H_\alpha+H_\epsilon) - \left(\frac{f}{4D}\right)_M \left(\frac{a}{g}\right)_M (v_\alpha|v_\alpha|-v_\epsilon|v_\epsilon|)\Delta t - \tfrac{1}{2}(v_\alpha+v_\epsilon)\sin\theta\Delta t \,. \quad (104)$$

Thus, using Equations(103) and (104) it is now possible to determine the velocity and pressure head, v_P and H_P, at each interior point on the x-t grid. The evaluation process advances with time throughout the bounded x-region.

It should be noted that the size of the increments Δx and Δt cannot be selected independently of each other. On the contrary, their size is integrally dependent. Since the finite difference solution scheme which has been outlined above converges to the exact characteristics solution as Δx approaches zero, one can conclude the following: (a) the values of v and H at any point P within the region of existence of the solution are determined solely by the initial values prescribed along

the segment of the x-axis subtended by the two characteristics passing through P , and (b) the two characteristics through P are themselves determined solely by the initial values on the segment. The segment of the x-axis determined by α and ϵ is, thus, the domain of dependence of the point P as shown in Figure 6. Therefore, when Δx is arbitrarily selected, Δt is automatically limited to an interval no larger in magnitude than that given by the relationship

$$\Delta t \leq \frac{\Delta x}{|v \pm a|} \quad .$$

In other words, the point P must lie within the region bounded by the intersecting characteristics curves through L and R and the subtended segment of the x-axis.

Boundary Conditions

The finite difference solution technique used with the characteristics equations must now be extended to include the various boundary conditions which are to be encountered.

Consider the situation at the right edge of Figure 7 in which only the positively directed characteristics curve C_+ is shown. One condition at point P_n is assumed to be given. This given condition may be either v_P or H_P . In order to calculate the unknown condition, it is necessary to first calculate v_α and H_α . The given boundary condition can then be used to determine the remaining unknown condition. Equations (97) and (98) are used to determine H_α and v_α . If v_P is the known boundary condition at point P_n , Equation (101) can be rearranged to give H_{P_n} ,

$$H_P = H_\alpha - (v_P - v_\alpha)\left(\frac{a}{g}\right)_M - \left\{\frac{f}{2D} v_\alpha |v_\alpha| + \left(\frac{g}{a}\right)_M v_\alpha \sin\theta\right\}\left(\frac{a}{g}\right)_M \Delta t \quad . \quad (105)$$

On the other hand, if H_P is given, this same equation may be rearranged to provide v_P at point n ,

$$v_P = v_\alpha - (H_P - H_\alpha)\left(\frac{g}{a}\right)_M - \left\{\frac{f}{2D} v_\alpha |v_\alpha| + \left(\frac{g}{a}\right)_M v_\alpha \sin\theta\right\}\Delta t \quad . \quad (106)$$

At the left end of the x-t grid shown in Figure 7, the C_- characteristicsgovern the unknown boundary value. Again one begins by calculating v_ϵ and H_ϵ from Equations (99) and (100). When v_P is the known boundary value at point P_1 , Equation (102) can be rearranged to provide H_P at P_1 ,

$$H_P = H_\epsilon + (v_P - v_\epsilon)\left(\frac{a}{g}\right)_M + \left\{\frac{f}{2D} v_\epsilon |v_\epsilon| - \left(\frac{g}{a}\right)_M v_\epsilon \sin\theta\right\}\left(\frac{a}{g}\right)_M \Delta t \quad (107)$$

and when v_P is the given boundary value at P_1 , Equation (102) is similarly rearranged to give

$$v_P = v_\epsilon + (H_P - H_\epsilon)\left(\frac{g}{a}\right)_M - \left\{\frac{f}{2D} v_\epsilon |v_\epsilon| - \left(\frac{g}{a}\right)_M v_\epsilon \sin\theta\right\}\Delta t \quad (108)$$

Now then, Equations (105-108) provide the boundary values appropriate for use in conjunction with the general Equations (103) and (104).

Attention must be given to the boundary conditions occurring at the junction between two pipes of different sizes and different materials. A typical portion of the x-t grid at such a junction is shown in Figure 8. In addition to the four boundary equations, Equations (105-108), already developed above, two other relationships prevail. These relationships are (1) the continuity-of-mass relationship, $v_I D_I^2 = v_{II} D_{II}^2$, and (2) the energy-equilibrium relationship, $H_I = H_{II}$. Minor losses at the

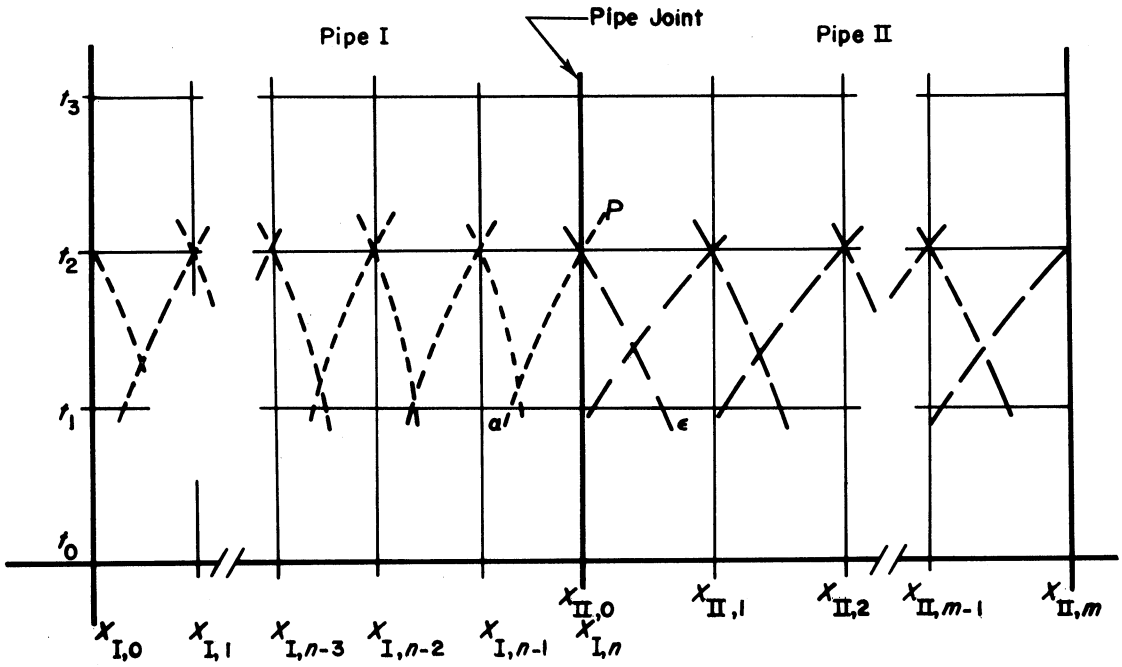

Figure 8. Definition Sketch Showing Relationship Between Space-Time Grids and Characteristics Curves at a Pipe Junction.

junction are ignored. Using the boundary equations one can derive an expression in v_{P_I} and H_{P_I} by adding Equations(105) and (106),

$$v_{P_I} + H_{P_I}\left(\frac{g}{a}\right)_{M_I} = v_\alpha + H_\alpha\left(\frac{g}{a}\right)_{M_I} - \left(\frac{f}{2D}\, v_\alpha |v_\alpha|\right)_{M_I} \Delta t - v_\alpha \sin\theta \left(\frac{g}{a}\right)_{M_I} \Delta t = \Psi \tag{109}$$

Similarly, Equations(107) and (108) may be subtracted and combined to give

$$v_{P_{II}} - H_{P_{II}}\left(\frac{g}{a}\right)_{M_{II}} = v_\epsilon - H_\epsilon\left(\frac{g}{a}\right)_{M_{II}} - \left(\frac{f}{2D}\, v_\epsilon |v_\epsilon|\right)_{M_{II}} \Delta t + v_\epsilon \sin\theta \left(\frac{g}{a}\right)_{M_{II}} \Delta t = X \tag{110}$$

Now, substituting $v_{P_I} = v_{P_{II}} \left(\frac{D_{II}}{D_I}\right)^2$ and $H_{P_I} = H_{P_{II}}$ into Equation (109),

$$\Psi = v_{P_{II}} \left(\frac{D_{II}}{D_I}\right)^2 + H_{P_{II}}\left(\frac{g}{a}\right)_{M_I},$$

and rewriting Equation (110),

$$X = v_{P_{II}} - H_{P_{II}}\left(\frac{g}{a}\right)_{M_{II}};$$

one can eliminate $v_{P_{II}}$

$$H_{P_{II}}\left[\left(\frac{g}{a}\right)_{M_I}\left(\frac{D_I}{D_{II}}\right)^2 + \left(\frac{g}{a}\right)_{M_{II}}\right] = \Psi \left(\frac{D_I}{D_{II}}\right)^2 - X$$

or

$$H_{P_I} = H_{P_{II}} = \frac{\Psi \left(\frac{D_I}{D_{II}}\right)^2 - X}{\left[\left(\frac{g}{a}\right)_{M_I}\left(\frac{D_I}{D_{II}}\right)^2 + \left(\frac{g}{a}\right)_{M_{II}}\right]} \tag{111}$$

Equations of Transient Motion-- Horizontal Pipe Flowing Partially Full

Transient liquid motion in a horizontal pipe flowing partially full, that is to say, flowing with a free surface, is comparable in many ways to the previously discussed transient liquid motion in a pipe flowing

full. Analytic treatment of the free surface flow as presented below will more clearly identify the similarities as well as the principal differences between the two types of transient motion.

Transient flow in a horizontal pipe having a free liquid surface is a function of two independent variables. These variables are the space and time variables, x and t, respectively; and are exactly comparable to the independent variables used previously with a pipe that is flowing full. Relative position in space is denoted by x as measured axially along the pipe. The gate valve is arbitrarily designated the point of zero reference. For pipe flow with a free surface the two dependent variables are the mean velocity of the free surface flow, u, and the depth of flow, z. In order to represent the variable velocities and depths, two quasi-linear, partial differential equations are developed and then transformed into four total differential equations--the characteristics equations of transient, open-channel flow. After being rewritten as finite difference equations in a manner comparable to the one used with the equations for the pipe flowing full, numerical methods are again introduced to enable evaluation by high-speed, digital computer. The governing boundary conditions are examined and interpreted analytically. The section concludes with a brief comparison of the similar analytic properties of transient, free-surface, pipe flow and transient liquid motion in a pipe flowing full.

Equation of Continuity

The net inflow of mass into a segment of free surface flow must equal the rate of mass increase taking place within the segment per unit

time. This statement sets forth the conservation of mass concept upon which the equation of continuity is based. Figure 9 shows an element of free-surface flow in a pipe. The element is bounded on the left and right by cross sections (2) and (1), respectively. For u equal to the mean velocity and A equal to the cross segmental area at cross section (1), the mass influx through this segment is ρAu. At cross section (2), flow leaves the element; therefore, the efflux of mass is given by

$$-[\rho Au + (\rho Au)_x dx] .$$

The net increase of mass in the control element per unit of time is

$$\rho Au - \left[\rho Au + \frac{\partial(\rho Au)}{\partial x} dx \right]$$

or

$$-\rho(Au)_x dx \tag{112}$$

The rate of mass increase occurring in the control segment per unit time is

$$\left[\frac{1}{2} (A + (A + \frac{\partial A}{\partial x} dx))\rho dx \right]_t$$

or

$$\frac{\rho}{2}[(A_t + A_t + \frac{\partial^2 A}{\partial x \partial t})dx]$$

or finally

$$\rho A_t dx \tag{113}$$

after higher order terms are eliminated.

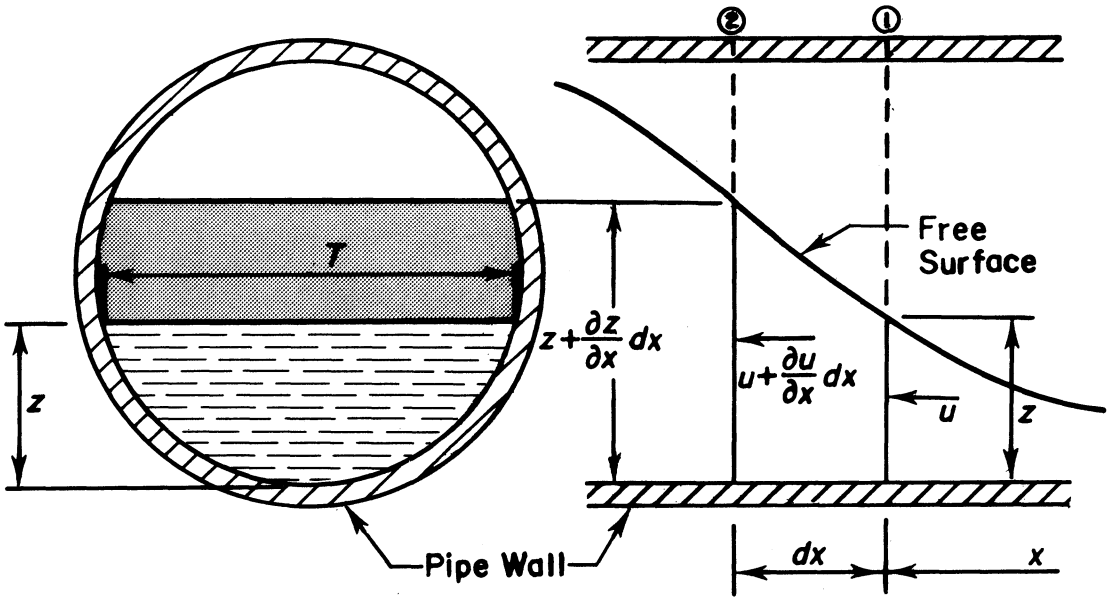

Figure 9. **Definition Sketch Illustrating** Element of Free-Surface Flow in a Pipe. Transverse Cross-Segment is Shown On the Left and Longitudinal Flow Profile is Shown On the Right.

The continuity equation may now be set forth by equating expressions (112) and (113) above:

$$- \rho(Au)_x dx = \rho(A_t)dx$$

or

$$\rho u A_x + \rho A u_x + \rho A_t = 0 \ . \tag{114}$$

Note that the small pressure changes associated with the changes in depth accompanying open-channel flow have no significant effect upon liquid density. Therefore, ρ is independent of both x and t.

The cross segmental area is a function of the flow depth, in other words, $A = A(z)$, and thus, $dA = Tdz$ where T is the surface width $2\sqrt{zD-z^2}$ and D is the inside pipe diameter. Moreover,

$$A_x = \frac{\partial A}{dz}\frac{\partial z}{\partial x} = T\frac{\partial z}{\partial x} = T z_x \ , \tag{115}$$

and by the same token

$$A_t = T z_t \ . \tag{116}$$

Equation (114) may now be written as

$$u z_x + \frac{A}{T} u_x + z_t = 0 \ , \tag{117}$$

which is the form of the continuity equation used in subsequent parts of the analysis.

Equation of Motion

The net flux of momentum from the control element and the time rate of change of momentum within the element must be instantaneously equivalent to the resultant of the external forces acting on the element.

The flux of momentum through cross section (1) in Figure 9 is actually an influx of momentum into the control element, namely $-\rho(Au^2)$. At section (2) the efflux of momentum is $+\rho(Au^2) + \rho\partial\frac{(Au^2)}{\partial x}dx$. Therefore, the net flux of momentum from the control element is

$$+\rho\frac{\partial(Au^2)}{\partial x}dx \quad . \tag{118}$$

The time rate of increase of momentum within the control element is

$$\left[\rho\left\{A + (A + \frac{\partial A}{\partial x}dx)\right\}\frac{1}{2}\left\{u + (u + \frac{\partial u}{\partial x}dx)\right\}\frac{1}{2}dx\right]_t$$

or simply

$$\rho(Au)_t\,dx \tag{119}$$

after all higher order terms have been eliminated.

The net hydrostatic pressure force, as is clearly illustrated in Figure 9, is

$$-\rho g(A + \frac{\partial A}{\partial x}dx)(\frac{\partial z}{\partial x}dx) \quad .$$

Once again higher order terms are eliminated to give

$$-\rho g A z_x dx \quad . \tag{120}$$

The flow resistance force may be attributed to the shear stresses developed at the pipe wall. It is given by

$$-\tau P_w dx \quad , \tag{121}$$

where P_w is the wetted perimeter and τ the boundary shear stress.

By equating the terms depicting a change in momentum to the force terms, one obtains the expression

$$+ \rho(Au^2)_x dx + \rho(Au)_t dx = - \rho g A z_x dx - \tau P_w dx$$

or

$$2\rho A u u_x dx + \rho u^2 A_x dx + \rho A u_t dx$$

$$+ \rho u A_t dx + \rho g A z_x dx + \tau P_w dx = 0 \ .$$

Division by $\rho A dx$ reduces this expression to simply

$$2uu_x + u^2 \frac{A_x}{A} + u_t + u \frac{A_t}{A} + g z_x + \frac{\tau}{\rho R_H} = 0 \ . \qquad (122)$$

The variable R_H represents the hydraulic radius. Because the shear stress can be defined as

$$\tau = \rho f \frac{u|u|}{8} \ , \qquad (69)$$

where f is again the pipe friction factor noted previously, the flow resistance term may be written

$$\tau P_w dx = f \frac{\rho u|u| P_w dx}{8} \ ,$$

after which, division by $\rho A dx$ leaves

$$\frac{\tau}{\rho R_H} = \frac{f u|u|}{8 R_H} \ . \qquad (123)$$

Equation 122 can now be rearranged to include this expression,

$$g z_x + u^2 \frac{T}{A} z_x + u \frac{T}{A} z_t + 2uu_x + u_t + \frac{f u|u|}{8R_H} = 0 \ . \qquad (124)$$

Write the continuity equation (Equation (117)) with each term multiplied by $u\frac{T}{A}$:

$$u^2 \frac{T}{A} z_x + u \frac{T}{A} z_t + uu_x = 0 \ . \tag{125}$$

Subtraction of Equation (125) from Equation (124) reduces the momentum equation to the form

$$gz_x + uu_x + u_t + \frac{fu|u|}{8R_H} = 0 \tag{126}$$

which is used in the subsequent parts of this analysis.

Characteristics Equations

The set of simultaneous, quasi-linear, hyperbolic, partial differential equations which describes transient liquid movement in a pipe flowing partially full, is rewritten below

$$\Gamma_3 = uz_x + z_t + \frac{A}{T} u_x = 0 \tag{127}$$

$$\Gamma_4 = gz_x + uu_x + u_t + \frac{fu|u|}{8R_H} = 0 \tag{128}$$

Linear combination of the expressions Γ_3 and Γ_4 produces

$$\Lambda = \Gamma_3 + m\Gamma_4 \tag{129}$$

or

$$\Lambda = mu_t + \left(\frac{A}{T} + mu\right) u_x + z_t + (u+mg)z_x + \frac{mfu|u|}{8R_H} \tag{130}$$

The dependent variables u and z are functions of the space and time variables x and t by assumption. As a result, if u and z are, in fact, solutions of Equations (127) and (128), then

$$du = \frac{\partial u}{\partial x}\, dx + \frac{\partial u}{\partial t}\, dt$$

or

$$\frac{du}{dt} = \frac{\partial u}{\partial x}\frac{dx}{dt} + \frac{\partial u}{\partial t} ,$$

and

$$dz = \frac{\partial z}{\partial x}\, dx + \frac{\partial z}{\partial t}\, dt$$

or

$$\frac{dz}{dt} = \frac{\partial z}{\partial x}\frac{dx}{dt} + \frac{\partial z}{\partial t} .$$

Therefore, Equation (130) can be written

$$\Lambda = m\frac{du}{dt} + \frac{dz}{dt} + m\frac{f}{8R_H}\, u|u| = 0 \qquad (131)$$

provided

$$\frac{dx}{dt} = \frac{\frac{A}{T} + mu}{m} = \frac{m(u+mg)}{m} . \qquad (132)$$

Equation (132) is valid if

$$\frac{du}{dt} = u_t + \frac{A}{mT} + u\ u_x \qquad (133)$$

and

$$\frac{dz}{dt} = z_t + (u+mg)\, z_x . \qquad (134)$$

If Equation (132) is now solved for m, one finds that

$$m = \pm\sqrt{\frac{A}{gT}} \qquad (135)$$

By substituting Equation (135) into Equations(131) and (132), two pairs of linear relations are determined, namely,

$$C_+ \begin{cases} 0 = -\sqrt{\frac{A}{gT}}\, du + dz + \sqrt{\frac{A}{gT}}\, \frac{f}{8R_H}\, u|u|dt = \Lambda dt & (136) \\ \frac{dt}{dx} = \frac{1}{u + \sqrt{\frac{Ag}{T}}} & (137) \end{cases}$$

and

$$C_- \begin{cases} 0 = -\sqrt{\frac{A}{gT}}\, du + dz - \sqrt{\frac{A}{gT}}\, \frac{f}{8R_H}\, u|u|dt = \Lambda dt & (138) \\ \frac{dt}{dx} = \frac{1}{u - \sqrt{\frac{Ag}{T}}} & (139) \end{cases}$$

which are total differential equations. These four equations are the characteristics equations governing the transient velocities and depths in a horizontal circular conduit flowing partially full.

In retrospect, Equation (136) simply states that there is a constant, velocity-depth relationship for a point whose motion in the x, t-plane is characterized by Equation (137). Likewise, a similar relationship exists between Equation (138) and (139). In other words, Equations (137) and (139) define the families of solution curves along which Equations(136) and (138) are valid.

Finite Difference Solution

The technique devised for finite difference solution of the characteristics equations depicting free-surface flow in a pipe is analogous to the technique described previously for solution of the characteristics equations representing liquid motion in a pipe flowing full. The size of

the stepping increment used in the solution is made small enough to insure that first order approximation is adequate.

The fact that any point on the x,t-plane is an intersection for a specific positive curve and a specific negative curve belonging to the respective families of characteristics curves associated with partial differential equations of the hyperbolic type is the basis for the solution technique. Figure 6 shows the intersection of a positive characteristics curve with a negative characteristics curve at P_i . Given the necessary initial and boundary conditions, it is the purpose of the solution technique to permit evaluation of mean velocity, u , and depth, z , at point P_i . In more general terms it must permit evaluation of u and z at any network of selected grid points on the x,t-plane, such as the rectangular grid illustrated in Figure 7.

Characteristics Equations, Equations (136)-(139), may be rewritten as follows:

$$C_+ \begin{cases} dt - \dfrac{dx}{u + \sqrt{\dfrac{gA}{T}}} = 0 \\ \\ dz + \sqrt{\dfrac{A}{gT}}\, du + \sqrt{\dfrac{A}{gT}}\, \dfrac{f}{8R_H}\, u|u|\, dt = 0 \end{cases} \tag{140}$$

$$C_- \begin{cases} dt - \dfrac{dx}{u - \sqrt{\dfrac{gA}{T}}} = 0 \\ \\ dz - \sqrt{\dfrac{A}{gT}}\, du - \sqrt{\dfrac{A}{gT}}\, \dfrac{f}{8R_H}\, u|u|\, dt = 0 \ . \end{cases} \tag{141}$$

If written in finite difference form these expressions become

$$(t_P - t_\alpha) - (x_P - x_\alpha)/(u + \sqrt{\frac{Ag}{T}})_\alpha = 0 \tag{142}$$

$$(z_P-z_\alpha) + \sqrt{\frac{A}{gT}}\,(u_P-u_\alpha) + \left(\sqrt{\frac{A}{gT}}\right)_\alpha \left(\frac{f}{8R_H}\,u|u|\right)_\alpha (t_P-t_\alpha) = 0 \qquad (143)$$

$$(t_P-t_\epsilon) - (x_P-x_\epsilon)/(u - \sqrt{\frac{Ag}{T}})_\epsilon = 0 \qquad (144)$$

$$(z_P-z_\epsilon) - \sqrt{\frac{A}{gT}}\,(u_P-u_\epsilon) - \left(\sqrt{\frac{A}{gT}}\right)_\epsilon \left(\frac{f}{8R_H}\,u|u|\right)_\epsilon (t_P-t_\epsilon) = 0 \qquad (145)$$

where the subscripts P, α, and ϵ refer to locations on the x,t-plane in Figure 7.

Values of u and z are assumed known, i.e., given initially or computed previously at all the grid points along the x-axis at prior to time t_{i-1}. Although the points on the grid are separated by specified space and time intervals, the locations of α and ϵ while known with respect to time are unknown with respect to x. These locations must be determined. If the solution is to advance with respect to time so that u_P and z_P can be determined at time t_i, the appropriate values of u and z at α and ϵ must be found first. This may be done using linear interpolation:

$$\frac{u_\alpha-u_L}{x_\alpha-x_L} = \frac{u_M-u_L}{x_M-x_L} = \frac{u_M-u_L}{\Delta x} \qquad (146)$$

$$\frac{u_R-u_\epsilon}{x_R-x_\epsilon} = \frac{u_R-u_M}{x_R-x_M} = \frac{u_R-u_M}{\Delta x} \qquad (147)$$

Now, by recognizing that $x_P = x_M$, and $t_M = t_\alpha = t_\epsilon$, Equations (142) and (144) can be written

$$x_M - x_\alpha = \left(u + \sqrt{\frac{Ag}{T}}\right)_\alpha (t_P-t_\alpha) = \left(u + \sqrt{\frac{Ag}{T}}\right)_\alpha \Delta t \qquad (148)$$

and

$$x_\epsilon - x_M = -\left(u - \sqrt{\frac{Ag}{T}}\right)_\epsilon (t_P-t_\epsilon) = -\left(u - \sqrt{\frac{Ag}{T}}\right)_\epsilon \Delta t\,, \qquad (149)$$

which represent the increment slopes of C+ and C- at α and ϵ, respectively. Equations (146) and (147) may be rewritten:

$$\left(\frac{u_\alpha - u_L}{u_M - u_L}\right)\Delta x = x_\alpha - x_L = \Delta x - (x_M - x_\alpha) \tag{150}$$

$$\left(\frac{u_R - u_\epsilon}{u_R - u_M}\right)\Delta x = x_R - x_\epsilon = \Delta x - (x_\epsilon - x_M) \tag{151}$$

Substitution of Equation (148) into Equation (150) and Equation (149) into Equation (151) gives Equations(152) and (153), respectively:

$$u_\alpha - u_L = (u_M - u_L)\left[1 - \left(u + \sqrt{\frac{Ag}{T}}\right)_\alpha \frac{\Delta t}{\Delta x}\right] \tag{152}$$

$$u_R - u_\epsilon = (u_R - u_M)\left[1 + \left(u - \sqrt{\frac{Ag}{T}}\right)_\epsilon \frac{\Delta t}{\Delta x}\right] \tag{153}$$

By using linear interpolation to determine z_α and z_ϵ, and then by reasoning in an analogous manner, the equations of depth complementing Equations(152) and (153) are found:

$$z_\alpha - z_L = (z_M - z_L)\left[1 - \left(u + \sqrt{\frac{Ag}{T}}\right)_\alpha \frac{\Delta t}{\Delta x}\right] \tag{154}$$

$$z_R - z_\epsilon = (z_R - z_M)\left[1 + \left(u - \sqrt{\frac{Ag}{T}}\right)_\epsilon \frac{\Delta t}{\Delta x}\right] \tag{155}$$

Hence, the desired values of u and z at α and ϵ become known:

$$u_\alpha = u_M + (u_L - u_M)\left(u + \sqrt{\frac{Ag}{T}}\right)_M \frac{\Delta t}{\Delta x} \tag{156}$$

$$z_\alpha = z_M + (z_L - z_M)\left(u + \sqrt{\frac{Ag}{T}}\right)_M \frac{\Delta t}{\Delta x} \tag{157}$$

$$u_\epsilon = u_M + (u_M - u_R)\left(u - \sqrt{\frac{Ag}{T}}\right)_M \frac{\Delta t}{\Delta x} \tag{158}$$

$$z_\epsilon = z_M + (z_M - z_R)\left(u - \sqrt{\frac{Ag}{T}}\right)_M \frac{\Delta t}{\Delta x} \quad . \tag{159}$$

Note that it is assumed that $\left(u+\sqrt{\frac{Ag}{T}}\right)_\alpha \approx \left(u+\sqrt{\frac{Ag}{T}}\right)_M$ and $\left(u-\sqrt{\frac{Ag}{T}}\right)_\epsilon \approx \left(u-\sqrt{\frac{Ag}{T}}\right)_M$, which is quite reasonable for a closely spaced rectangular grid.

Mean velocity and depth at point P_i can now be computed. Equations (143) and (145) are rewritten

$$(z_P-z_\alpha)+\left(\sqrt{\frac{A}{gT}}\right)_M(u_P-u_\alpha)+\left(\sqrt{\frac{A}{gT}}\right)_M\left(\frac{f}{8R_H}u|u|\right)_\alpha \Delta t = 0 \quad (160)$$

$$(z_P-z_\epsilon)-\left(\sqrt{\frac{A}{gT}}\right)_M(u_P-u_\epsilon)-\left(\sqrt{\frac{A}{gT}}\right)_M\left(\frac{f}{8R_H}u|u|\right)_\epsilon \Delta t = 0 , \quad (161)$$

then added to find z_P,

$$2z_P = (z_\alpha+z_\epsilon)+(u_\alpha-u_\epsilon)\left(\sqrt{\frac{A}{gT}}\right)_M-\left(\frac{f}{8R_H}\right)_M(u_\alpha|u_\alpha|-u_\epsilon|u_\epsilon|)\left(\sqrt{\frac{A}{gT}}\right)_M \Delta t$$

$$z_P = \frac{1}{2}(z_\alpha+z_\epsilon)+\frac{1}{2}(u_\alpha-u_\epsilon)\left(\sqrt{\frac{A}{gT}}\right)_M-\left(\frac{f}{16R_H}\right)_M(u_\alpha|u_\alpha|-u_\epsilon|u_\epsilon|)\left(\sqrt{\frac{A}{gT}}\right)_M \Delta t \quad (162)$$

and subtracted to find u_P

$$2u_P = u_\alpha+u_\epsilon+(z_\alpha-z_\epsilon)\left(\sqrt{\frac{gT}{A}}\right)_M-\left(\frac{f}{8R_H}\right)(u_\alpha|u_\alpha|+u_\epsilon|u_\epsilon|)\Delta t$$

$$u_P = \frac{1}{2}(u_\alpha+u_\epsilon)+\frac{1}{2}(z_\alpha-z_\epsilon)\left(\sqrt{\frac{gT}{A}}\right)_M-\left(\frac{f}{16R_H}\right)(u_\alpha|u_\alpha|+u_\epsilon|u_\epsilon|)\Delta t . \quad (163)$$

Clearly, it is now possible to determine the velocity and depth of the free surface flow at any interior point on the x-axis not only at time t_i but at all times after t_i simply by repetitively using Equations (156)-(159) together with Equations (162) and (163).

As previously pointed out while developing the finite difference solution for the pipe flowing full, the size of the increments Δx and Δt are interdependent. The same is true of the Δx and Δt increments

of free-surface pipe flow. With reference to Figure 6, the segment of the x-axis bounded on the left at α and on the right by ϵ is the domain of dependence of the point P_i. Thus, whenever Δx is arbitrarily selected, Δt is limited to an increment of magnitude no larger than

$$\Delta t \leq \frac{\Delta x}{(|u| + \sqrt{\frac{Ag}{T}})} \quad .$$

Another way of expressing this is to specify that any point P at which u_P and z_P are to be computed must lie within the domain of dependence bounded by the characteristics curves, C+ and C- , passing through L and R , respectively. Figure 10 graphically illustrates the significance of this requirement.

Boundary Conditions

At the right edge of Figure 7 where $x = x_n$ only one characteristicscurve, C+ , is shown. This curve passes through the boundary point P_n. One value, either u_P or z_P is assumed to be given at this point. By first calculating u_α and z_α from Equations(156) and (157), the given boundary value can then be used to determine the unknown value. Suppose that u_P is the known value. Then Equation (160) can be rewritten to give z_P ,

$$z_P = z_\alpha - (u_P - u_\alpha)\left(\sqrt{\frac{A}{gT}}\right)_M - \left(\frac{f}{8R_H}\, u|u|\right)_\alpha \left(\sqrt{\frac{A}{gT}}\right)_M \Delta t \quad . \qquad (164)$$

If z_P is the known boundary condition, then Equation (160) can be rewritten

$$u_P = u_\alpha - (z_P - z_\alpha)\left(\sqrt{\frac{gT}{A}}\right)_M - \left(\frac{f}{8R_H}\, u|u|\right)_\alpha \Delta t \quad . \qquad (165)$$

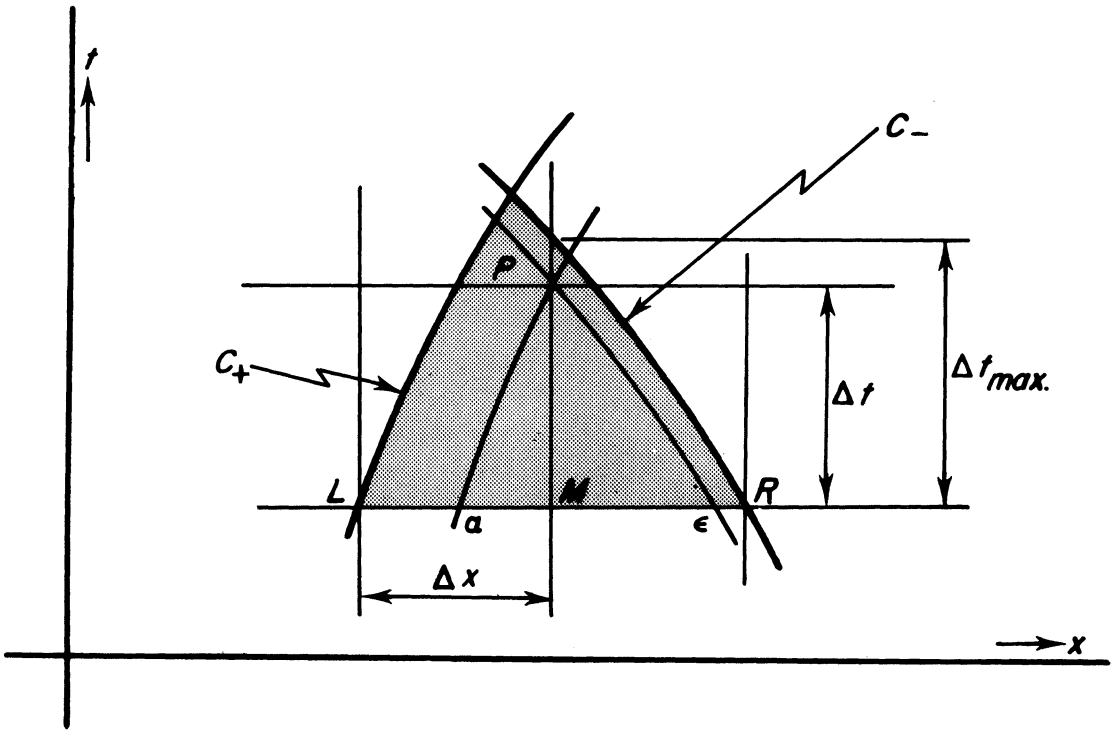

Figure 10. Definition Sketch Illustrating Domain of Dependence Governed by Characteristics Passing Through Grid Points L and R . Point P Must Lie Within Region Bounded by Line Segment LR and Characteristics Curves C+ and C- .

At the left edge of Figure 7 where only one characteristics curve, C- , passes through P_o the analogous boundary condition equations can be found using Equations(158) and (159) with Equation (161), first for u_P known and then for z_P known:

$$z_P = z_\epsilon + (u_P - u_\epsilon)\left(-\sqrt{\frac{A}{gT}}\right)_M + \left(\frac{f}{8R_H}\, u|u|\right)_\epsilon \left(-\sqrt{\frac{A}{gT}}\right)_M \Delta t \qquad (166)$$

$$u_P = u_\epsilon + (z_P - z_\epsilon)\left(-\sqrt{\frac{gT}{A}}\right)_M - \left(\frac{f}{8R_H}\, u|u|\right)_\epsilon \Delta t \ . \qquad (167)$$

Before concluding this chapter, it is certainly worth noting the very pronounced similarity between the equations of transient motion for the pipe flowing full and the equations of transient motion for a horizontal pipe with free surface flow. The latter is analogous to unsteady, open-channel flow. By comparing Equation (72) with Equation (127) and Equation (71) with Equation (128), one becomes clearly aware of this similarity. The similarity is further evidenced by comparing the respective sets of characteristics equations, namely, Equations (79)-(82) and Equations (136)-(139).

Note that in the closed pipe the celerity of the internal pressure wave is

$$\sqrt{\frac{1}{\rho\left(\frac{1}{K} + \frac{C}{E}\left(\frac{R}{b-R}\right)\right)}}$$

On the other hand in a pipe undergoing flow with a free surface, the celerity of the infinitesimal surface wave--a pressure wave in the external sense--is given by the expression $\sqrt{\frac{Ag}{T}}$. In each instance the celerity is affected by the particular properites of the liquid. It is also affected by the particular liquid-solid and/or liquid-gas interface conditions.

When the pipe is flowing full the celerity is a function of the pipe constraint and elasticity as well as the liquid properties, whereas, when the pipe is flowing partially full the celerity is a function of the shape-geometry of the flow and of the liquid properties. Nevertheless, both expressions are dimensionally similar.

When one recognizes that transient flow conditions in a pipe flowing full on the one hand and in a pipe flowing with a free surface on the other hand are basically very similar hydrodynamic phenomena, then the similarity of the respective analytic treatments and mathematical results is not surprising. However, recognition of the hydrodynamic similarity has been delayed perhaps, by the traditional division of hydrodynamics into "pipe-flow" problems and "open-channel" problems.

CHAPTER IV

COMPUTER SIMULATION

Column separation precipitated by transient flow in a pipe was interpreted theoretically in Chapter II. Its two principal regimes of liquid motion were the subjects of analysis which included the development of numerical processes for their evaluation in Chapter III. In this chapter the theoretical concepts of transient-flow, column separation phenomenon, and the mathematical treatment of its two regimes of liquid motion are used to formulate a working mathematical model for simulating the phenomenon by digital computer. The specific boundary criteria applicable to the model are discussed in detail. The sequence of operations followed in the model is described and presented by means of a flow chart. The structure of the computer program is discussed briefly. The chapter concludes with several general remarks about the operational characteristics of the simulation model.

Flow System

The flow system envisioned for computer simulation of the transient flow, column-separation phenomenon is physically similar to the example system considered in Chapter II (See Figure 2). A constant-head reservoir and a quick-closing gate valve are assumed to be connected by a long length of pipe. The reservoir is open to atmospheric pressure. The gate valve is capable of instantaneous closure. Its elevation, however, is variable with respect to that of the reservoir. The long length of pipe connecting the reservoir to the valve is composed of two (or more) pipe segments, each of which may be of unique diameter,

wall-thickness, length, composition, and may have different friction-loss properties as well as support fixity. The pipe segment connected to the gate valve is the one in which column separation is anticipated. This segment remains horizontal at all times; the other segments are free to assume any inclined position. Because axial distance along the pipe system is measured from the valve, this segment is denoted as segment No. 1. Figure 11 shows a schematic drawing of the flow system.

Initially, the gate valve is assumed to be fully open, thereby permitting steady flow throughout the system. At some time prior to the reference or starting time, t_0, the velocities and pressure heads on the x,t-plane at the particular points, $x_{k,i}$, are determined from steady-state conditions. These quantities are the initial conditions used to begin simulation of the transient-flow, column-separation phenomenon in the computer model. The notation, k, is an integer subscript denoting the particular pipe segment.

Boundary Conditions

The purpose of this discussion is to identify and set forth the controlling boundary conditions which delimit a unique, well-defined solution of the mathematical model. Without an explicitly stated set of boundary conditions, accurate computer simulation of the transient-flow, column-separation phenomenon observed in a prototype system would be impossible.

Prior to closure of the gate valve two boundary conditions govern steady-state flow in the system: pressure head at the entrance to the pipe and the velocity of flow through the gate valve. Since the constant head reservoir is unable to sustain a pressure other than its

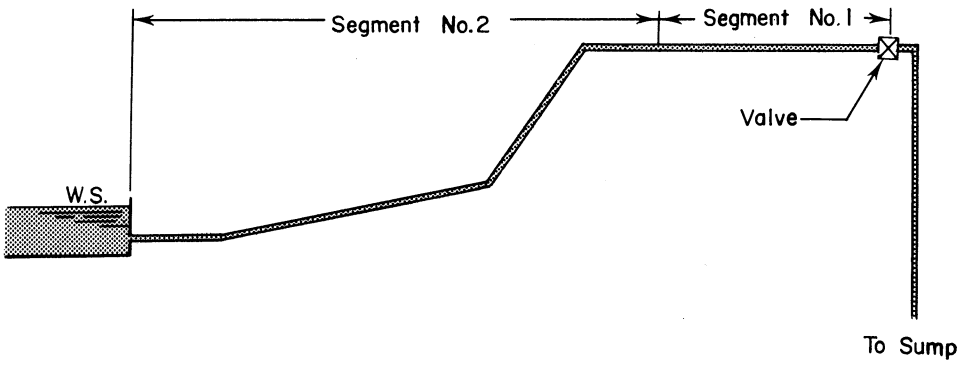

Figure 11. Schematic Representation of Laboratory Flow System Used in Experimental Investigation.

own static pressure head, $H_{k,n}$ is known and constant throughout time. The velocity through the gate valve is equivalent to simply the discharge divided by the area of the cross section at the valve; therefore, $v_{1,0}$ is known, also. $H_{k,n}$ and $v_{1,0}$ are "given" boundary conditions which are used with Equations(105) and (108) in the numerical evaluation process to determine $v_{k,n}$ and $H_{1,0}$.

Transient-flow conditions are initiated by closure of the gate valve. This occurs at time t_0. Therefore, $v_{1,0}$ is set to zero at time t_0 and remains zero until column separation takes place. However, the pressure head, $H_{k,n}$, at the reservoir remains unchanged and continues to be the second boundary condition needed to define this phase of the flow.

When the pressure head $(H_{1,0})$ at the gate valve falls to the vapor pressure of the water, column separation takes place. At the instant of column separation, new boundary conditions must be defined for the pipe flowing full and another set of boundary conditions introduced to describe conditions governing the free-surface flow in the pipe.

For the pipe flowing full the pressure head at the reservoir, $H_{k,n}$, remains unchanged. However, the boundary condition which formerly governed the condition of flow at the gate valve is now located at the moving interface separating the full flow regime from the free-surface flow regime within the pipe. This boundary condition is $H_{1,0}$ set equal to the water-vapor pressure head where the subscript zero now refers temporarily to the position of the interface. Thus, $H_{k,n}$ and $H_{1,0}$ are used with Equations(108) and (106) to determine $v_{k,n}$ and $v_{1,0}$ at the boundaries of the full-flow system.

One of the conditions governing the free-surface flow occurring in pipe segment No. 1 is the boundary condition at the gate valve. Because the gate valve is closed there can be no flow (with a free-surface or otherwise) through the valve; thus, the boundary condition is simply that the velocity u_0 equal zero. However, a second boundary condition, which suitably pertains to the condition of flow at the interface between the two regimes of liquid motion is not so easily reconciled. A condition is needed prescribing either the velocity of flow or the depth of water at the leading edge of the free surface interface. But because the forefront of the cavity is itself moving with time, this task is formidable.

Repeated laboratory observations of column separation revealed that the leading edge of the cavity appeared to separate from the topmost, inner surface of the pipe wall in a manner which remained basically unchanged regardless of the prior velocity of flow. In fact, the foremost edge of the cavity appeared to maintain a profile of more-or-less constant parabolic shape (See Figure 1). Although the mechanism of liquid separation from the pipe wall is not investigated in this study, local surface tension is thought to be the principal factor governing its behavior. The mechanism of liquid separation from the pipe wall, while fundamentally a three-dimensional flow process, can be adequately treated as a one-dimensional flow process provided the pipe diameter is not too small. Thus, if the foremost tip of the advancing vapor cavity is assumed to actually have a parabolic profile, a means is at hand by which the boundary condition, z_m, can be prescribed.

In the simulation model the shape of the advancing tip of the vapor cavity is assumed to be analytically represented by the similarly shaped void subtended by a parabolic cylinder which intersects at right angles with a circular cylinder, i.e., the pipe, as shown in Figure 12. The equation of the parabola on the x, z-plane is

$$(z - 2R(1-\theta))^2 = 4x_p(-\theta R) ,$$

wherein the focal distance, cb , is θR ; the latus rectum, ad , is $4\theta R$; and the vertex, located on the Z axis, is offset from the X axis by the distance $2R(1-\theta)$. The horizontal length of the subtended void as measured from the vertex of the parabolic cylinder is the variable, x_p , while θ is a preselected decimal parameter. The depth, z , at any point on the surface of intersection depicting the free-surface profile at the forefront of the cavity is given by

$$z = 2R(1-\theta) \mp \sqrt{4\theta R x_p} . \qquad (168)$$

The hypothesis advanced in Chapter II asserts that the volume rate-of-growth of the vapor cavity is equivalent to the full-flow discharge that occurs in the pipe immediately ahead of the cavity. Thus, since $v_{1,0}$ can be found by computation and since the pipe diameter is known, the equivalent volume rate-of-growth of the cavity can be determined.

The subtended parabolic void representing the forefront of the cavity takes form at the gate valve, that is, at x_0 . It expands in volume and length with time. As soon as its volume is sufficient to insure an overall length greater than Δx , thus causing it to extend

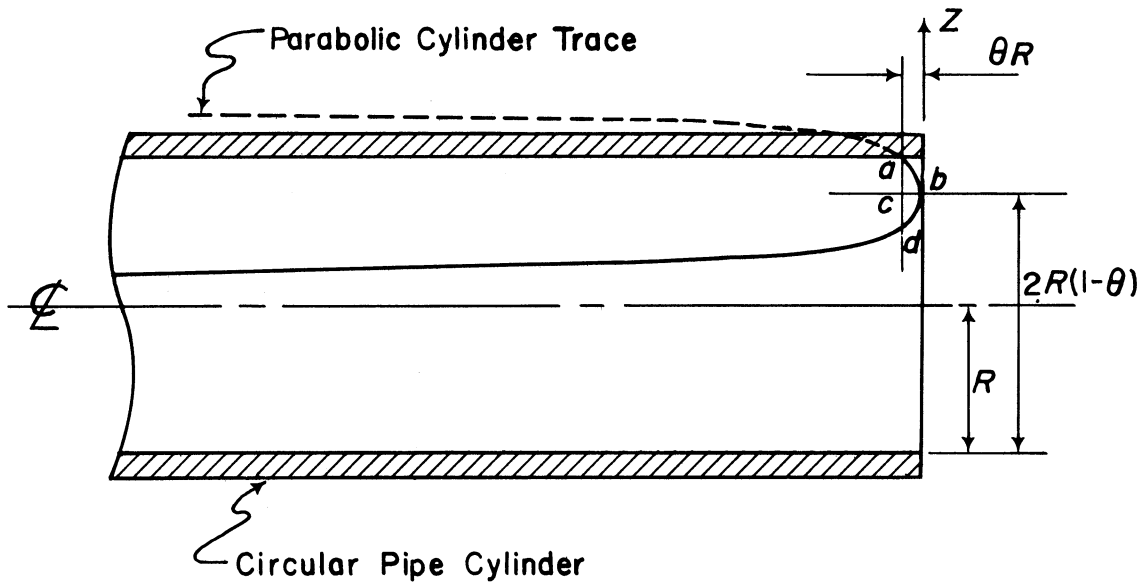

Figure 12. Definition Sketch Showing a Parabolic Cylinder Intersecting a Circular Cylinder. The Shape of the Common Volume Resulting from this Intersection is Considered Representative of the Shape of the Void Typically Encountered at the Leading Edge of the Vapor Cavity.

beyond x_1, the value of z_0 and z_1 can be determined from Equation (168). As previously stated u_0 equals zero. The velocity u_1 is arbitrarily set equal to $v_{1,0}$, which although an approximation must be very nearly correct. Thus, the initial velocity and depth of the embryonic, free-surface flow at x_0 and x_1 are now known at some time t_i on the x,t-plane. These values serve as "given conditions" with which the characteristics evaluation process can be initiated to compute the changing values of velocity and depth at subsequent intervals in time.

Meanwhile, of course, the actual vapor cavity is continuing to lengthen and increase in total volume. At x_0 the boundary condition $u_0 = 0$ remains unchanged. Although the characteristics evaluation process can be used to simulate the free-surface depths and flow velocities, the boundary depth, z_m, farthest from the gate valve (in other words, the depth at the grid point nearest the cavity tip) must be determined. This boundary depth is computed recursively with time by means of the parabolic-void approximation. However, it is worth noting that this approximation affects only the tip-most portion of the simulated vapor cavity, chiefly that portion of the cavity extending beyond the farthest, free-surface grid point on the x axis. The parabolic void approximation is used to approximate the depth during both the growth and collapse phase of the cavity simulation process. Thus, with the exception of some slight distortion which perhaps may be introduced by the boundary condition imposed at the forefront of the vapor cavity, a well-defined technique for mathematically simulating the column separation accompanying transient flow in pipes is available.

Sequence of Operations

The model employed to mathematically simulate the phenomenon of transient flow in a pipe and the accompanying phenomenon of liquid column separation consists of a multitude of individual operations performed in a specifically prescribed, logical sequence. The operations may be grouped into general categories which are related to particular functions. These functional categories are listed sequentially:

(a) Introduction, predefinition, and initialization of specific parameters, constants, and control factors used in the simulation model.

(b) Establishment of the theoretical flow system including initialization of the pre-transient regimen for the pipe system (pipe flowing full).

(c) Delineation of the boundary conditions and operating controls determining the transient flow phenomenon in the pipe system.

(d) Successive calculation of the transient velocities and depths throughout the system with respect to time while the pipe is flowing full. The method of characteristics is used to carry out these calculations. Special means are employed to apply the method when the increment Δx equals the overall length of a pipe segment.

(e) Determination of the occurrence of column separation by means of test conditions. Certain control parameters are set up in order to integrate an additional sequence of operations to be followed during periods of separation.

(f) Predefinition of functions and computation of initial values and boundary conditions governing free-surface flow.

(g) Computation of transient free-surface velocities and depths associated with the growth and collapse of the vapor cavity. The computations are carried out by the method of characteristics for free-surface flow concurrently with the calculation for the pipe flowing full.

(h) Reinitialization of both major and minor control parameters and boundary conditions following collapse of the vapor cavity.

An abbreviated schematic flow diagram depicting the sequence of operations followed in the simulation process is presented in Figure 13. Much of the mathematical detail has been eliminated from the diagram in order to emphasize the logic of the simulation process.

Digital Computer Program

The digital computer program used to transmit the statement of the model simulating the transient-flow, column-separation phenomenon to the computing machine follows the skeletal structure outlined in the flow diagram. The actual computer program is composed of a main program and several subprograms, which when integrated make up the whole program. The main program performs the functions outlined in the flow diagram. Consequently, it is structured similarly. Eleven subprograms or subroutines were written to perform various operations required by the main program. These subroutines are called upon as needed. In addition, six internal subroutines are defined and embedded in the main program.

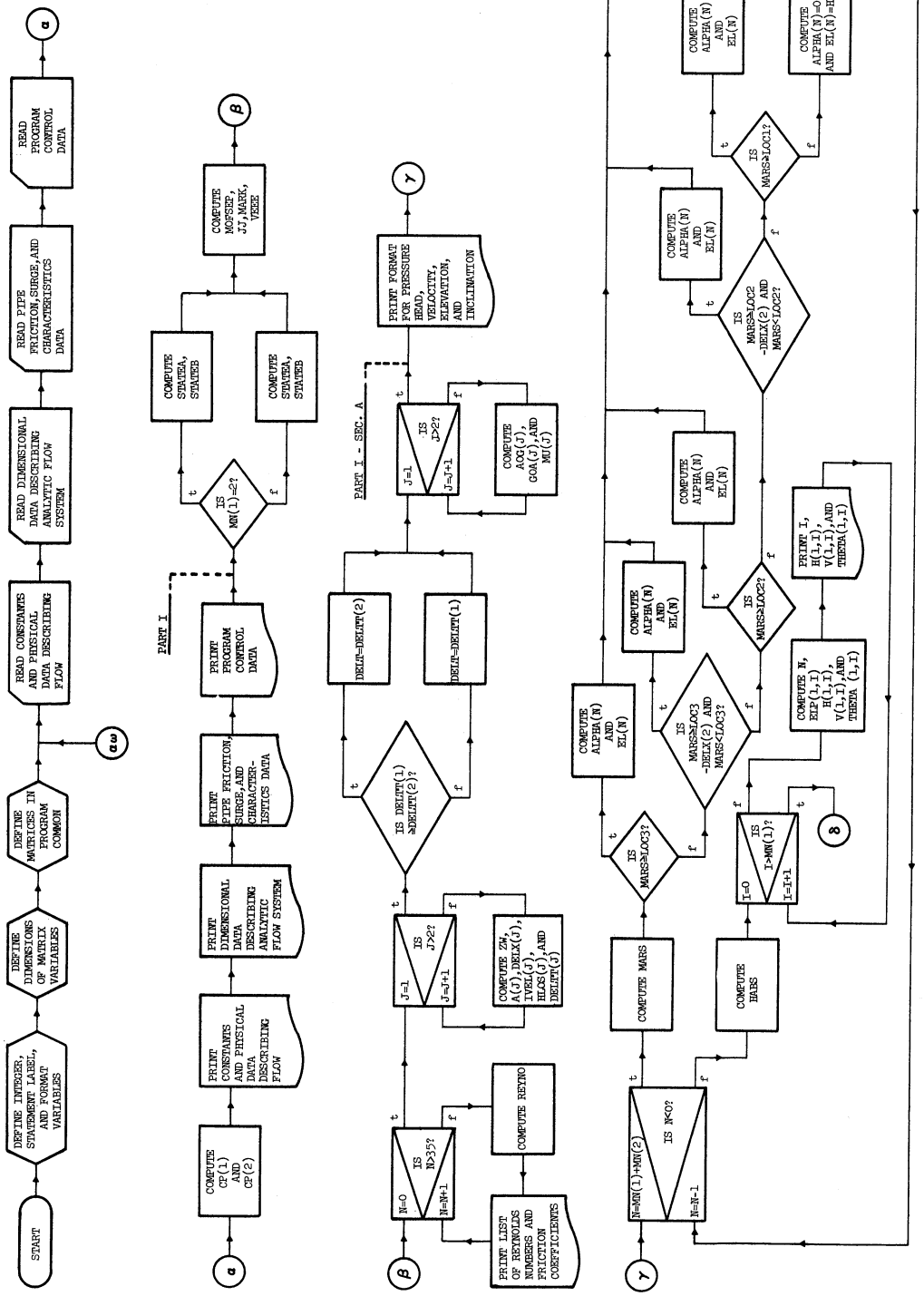

Figure 13. An Abridged Flow Diagram Setting Forth the Sequence of Operations Used to Simulate Transient Pipe Flow and the Accompanying Column Separation.

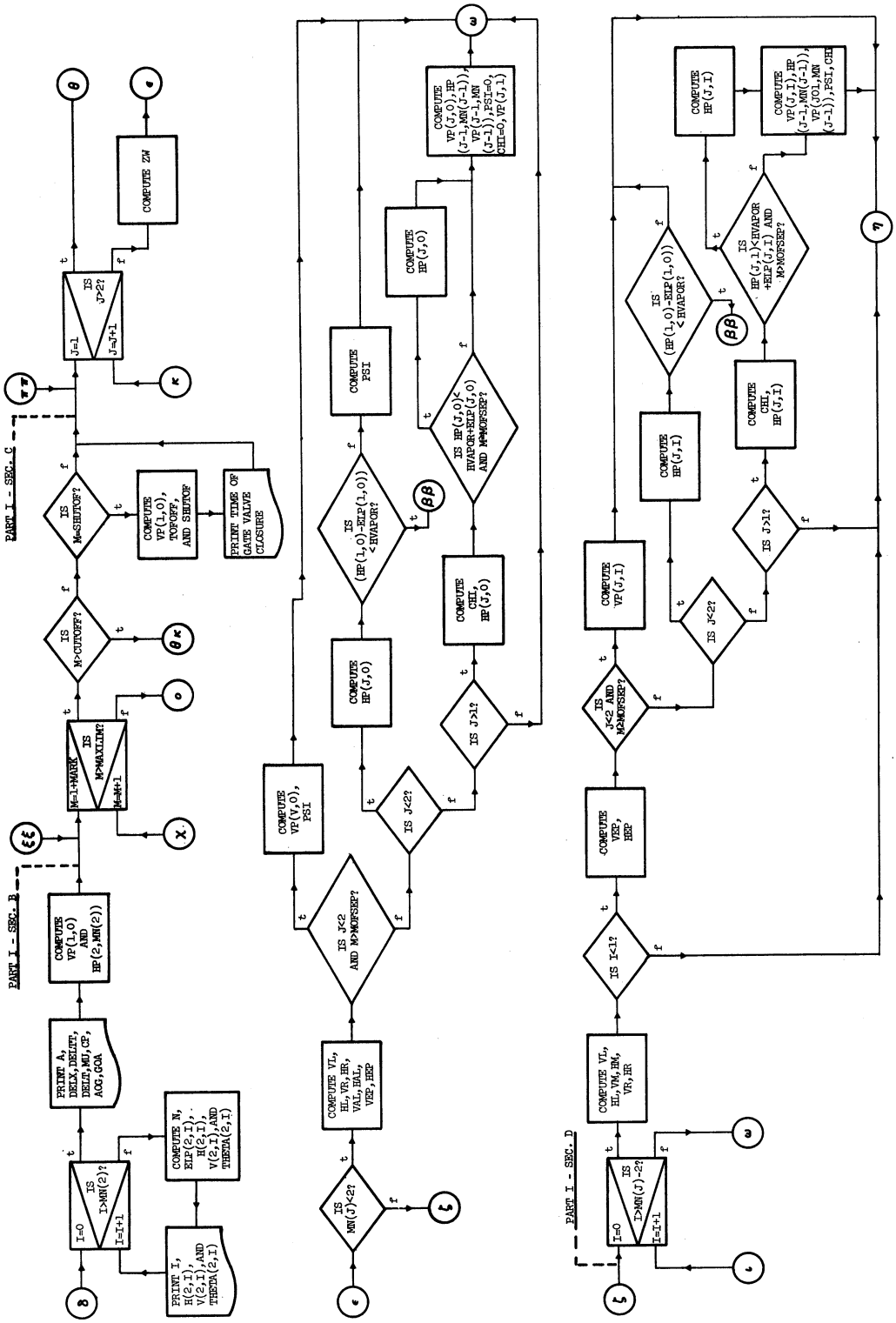

Figure 13. (Cont'd)

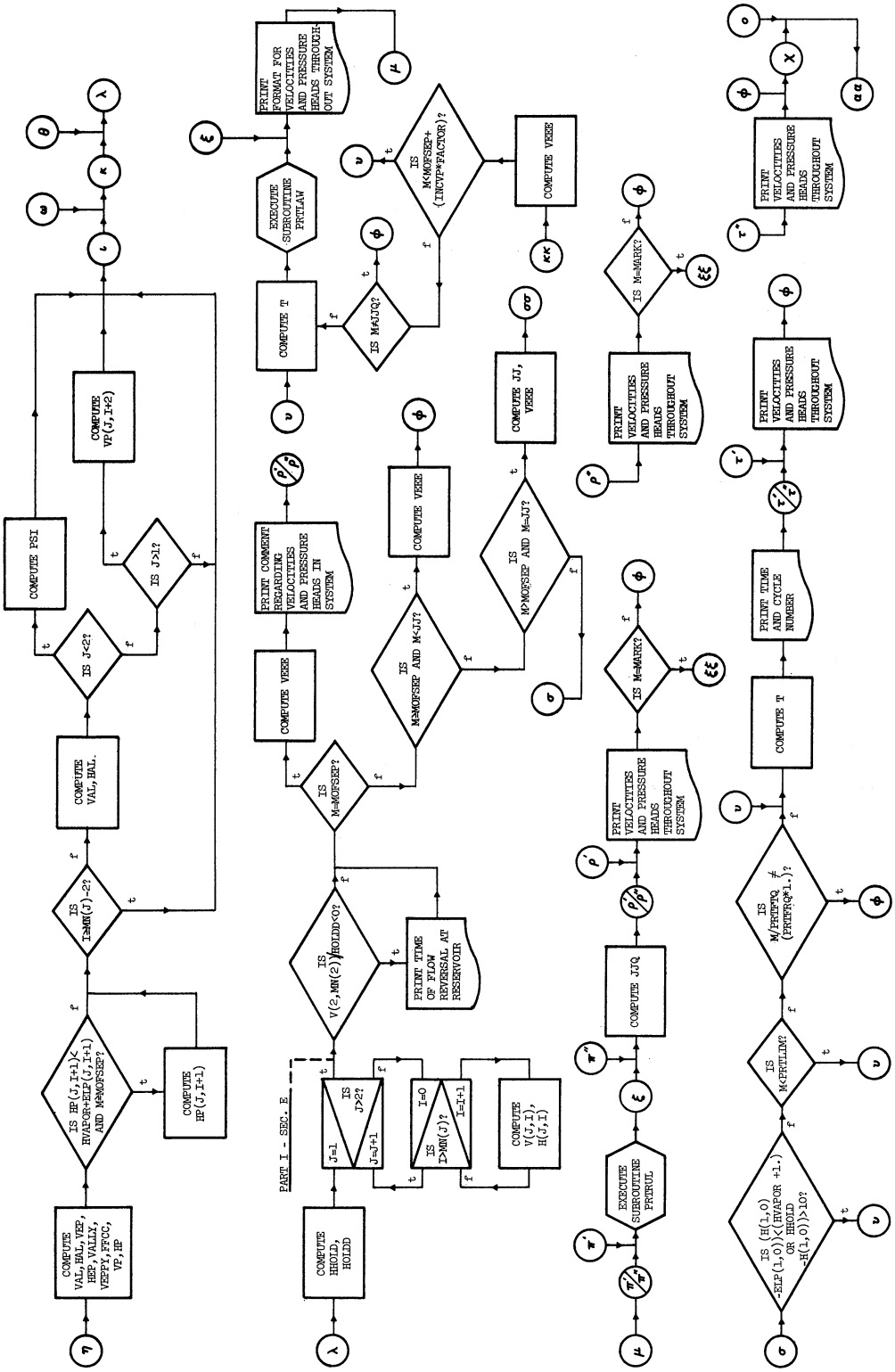

Figure 13. (Cont'd)

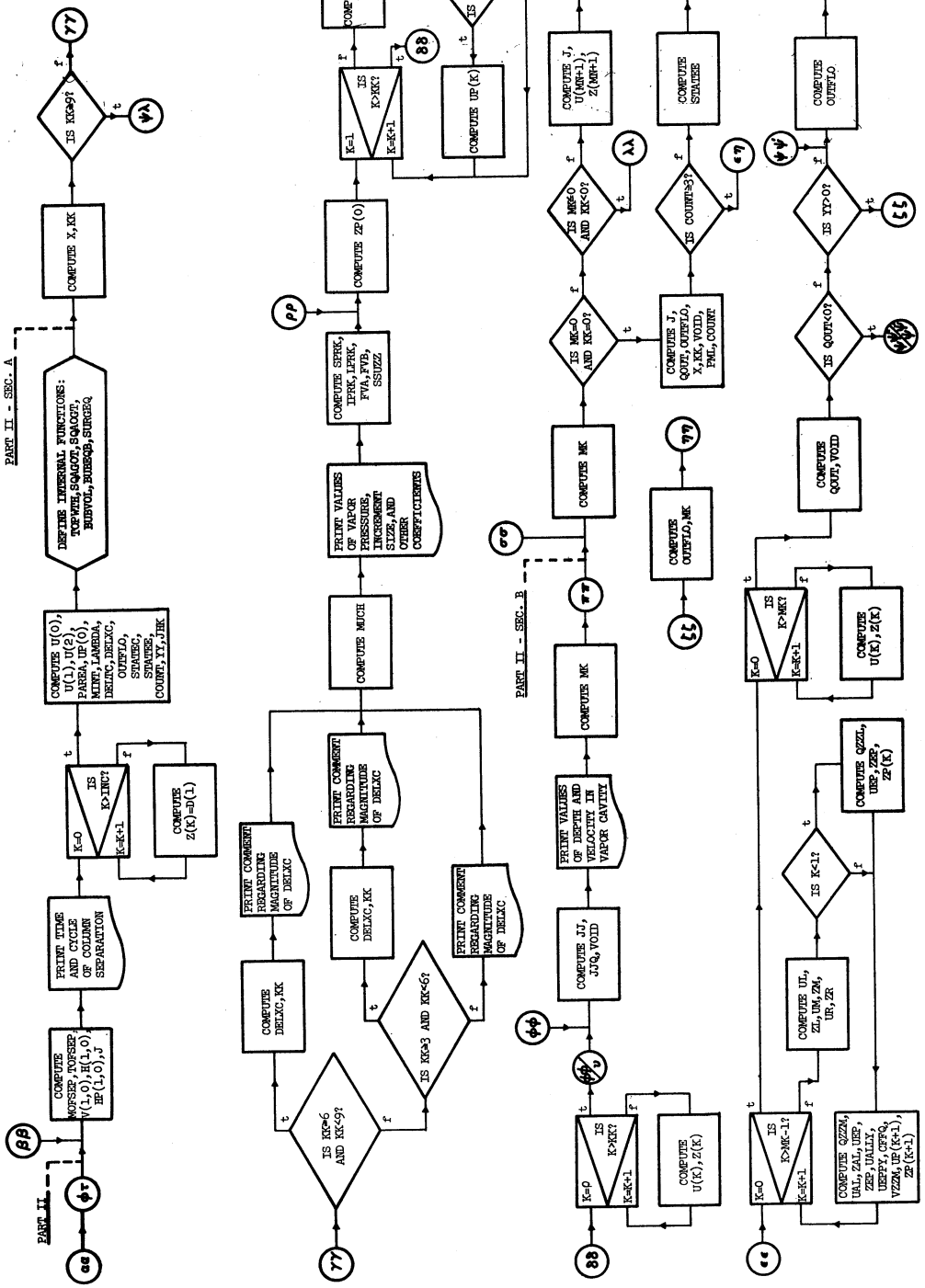

Figure 13. (Cont'd)

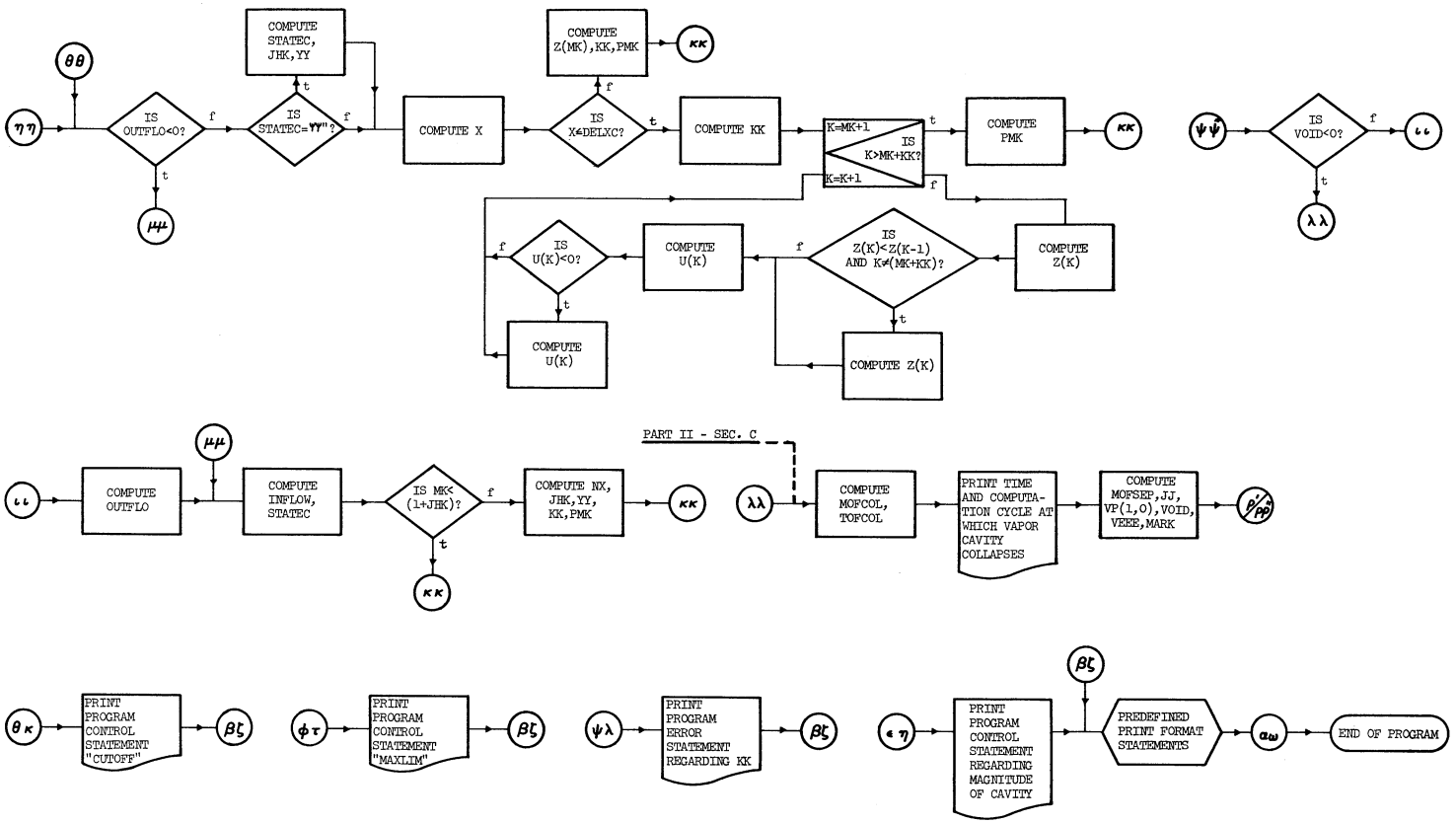

Figure 13. (Cont'd)

Consider the fact that in the particular prototype flow system being simulated, the elapsed time, starting with the moment transient flow is initiated, continuing through the ensuing formation of the first vapor cavity, and concluding with its collapse, is approximately two or three seconds. If the digital computer could simulate this portion of the phenomenon in less than actual time, it would be performing in so-called "fast time." If it required exactly the same number of seconds it would be performing the simulation in "real time." If the computer required longer than the actual time to complete the simulation run, it would be performing in "slow time." Because the ratio of the actual time to that required to simulate the separation phenomenon was approximately 1 to 240, the digital computer simulated column separation in slow time.

The computer program (the main program and special subroutines) is written in the Michigan Algorithm Decoder language commonly known as MAD. This language is an enriched Algol base compiler language which has been designed for implementation on IBM 7090 series computing systems having 32K words of main memory. Certain of the operational characteristics of the program experienced for the particular system configuration investigated are tabulated below:

(a) Required locations in main memory

Main program--8,139 words

Special subroutines--1,639 words

Complete program--17,390 words

(b) Total comilation time of complete program--127 seconds

Complete listings of the main program and of the subroutines are given in Appendices I and II, respectively.

CHAPTER V

EXPERIMENTAL APPARATUS AND LABORATORY INVESTIGATION

Experimental investigation of the column separation phenomenon comprises the second major phase of this study. It serves to complement the theoretical analysis which culminated in the technique for computer simulation of column separation discussed in Chapter IV. Experimental investigation was carried out in a specially constructed pipe system located in the G. G. Brown Fluids Engineering Laboratory on the North Campus at The University of Michigan. This chapter describes the pipe system and the special instrumentation and apparatus used in the laboratory investigation. It also treats the determination of the resistance-to-flow characteristics of the pipe system as well as the calibration of the instrumentation used to measure transient pressure and depth-of-flow. The chapter concludes with a summary of the procedures followed in conducting the experimental measurements.

General Description of Pipe System

The laboratory flow system was comprised of four principal elements: a constant-head weir box; approximately 439 feet of heavy-duty, one-inch inside diameter copper pipe; approximately 8.5 feet of one-inch inside diameter plexiglas (cast acrylic resin) pipe; and a solenoid-operated, quick-closing gate value. The weir box was connected to the gate valve by means of the copper pipe and the plexiglas pipe. The plexiglas pipe served as the test section in which the anticipated column separation could be observed. It was therefore connected directly to the

gate valve. Water was supplied to the weir box from the laboratory supply and returned to a sump by means of a copper pipe and a heavy duty hose. Siphon action was used to maintain flow through the system. A detailed sketch of the flow system is presented in Figure 14.

The constant-head, weir box was designed to minimize the fluctuations in head caused by changes in the discharge in the pipe system. Two sharp-crested, horizontal, overflow weirs were provided such that if a maximum flow velocity of 3 ft./sec. in the system were suddenly reduced to zero, the maximum increase in head in the box would be less than .011 ft. A manifold was used to introduce water into the weir box with minimum turbulence.

The copper pipe was composed of six segments carefully joined together to form a continuous conduit. A short segment only 1.25 feet in length and integrally attached to the constant-head weir box, serves as the inlet. The next four segments, each approximately 100 feet in length, were joined by soldered sleeve connections. To conserve space these segments were loosely coiled in a helix 5 feet in diameter and supported by a finger-like wooden frame mounted vertically upon a mobile hexagonal platform. The pipe was not constrained by the frame, therefore the coils could freely adjust to imposed strains. Figure 15 shows the constant-head weir box and the coiled pipe on the supporting frame. The final segment of copper pipe extended approximately 37.5 feet from the top of the coil to its junction with the plexiglas pipe. The properties of the various segments of copper pipe used in the system are listed in the table below:

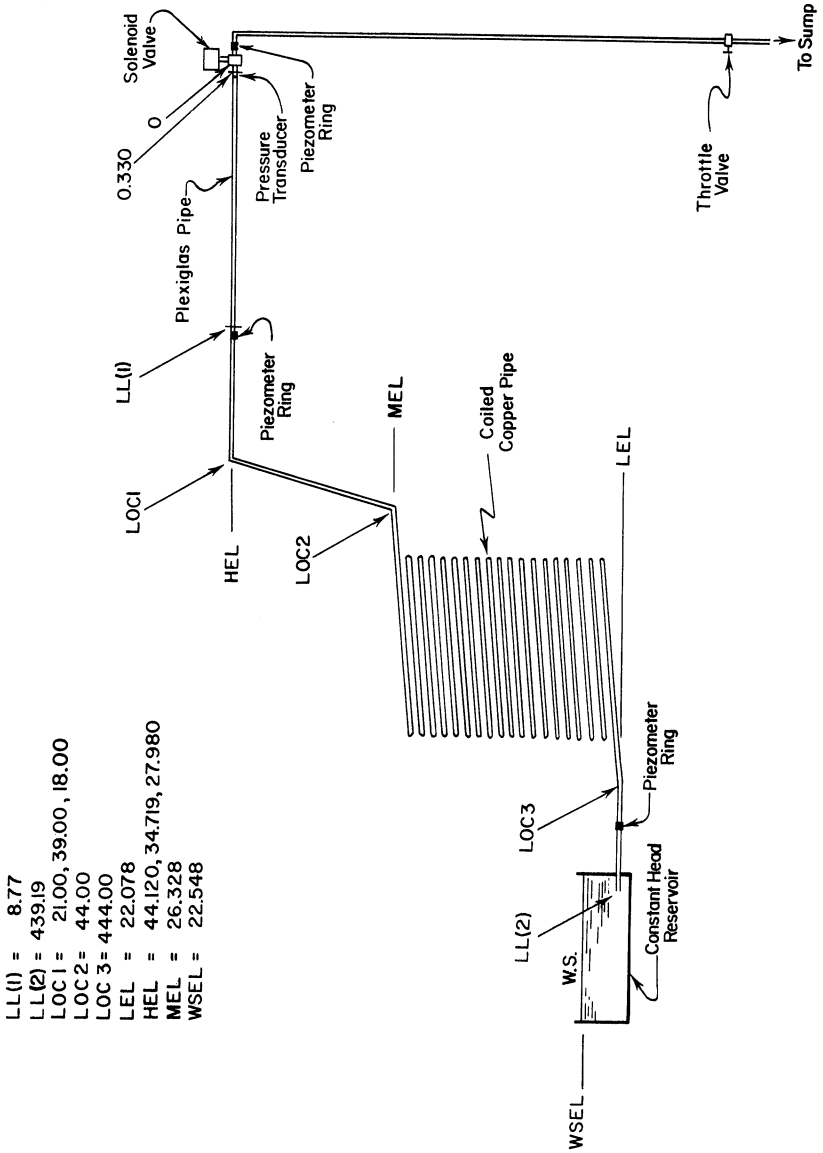

Figure 14. Detailed Schematic of Laboratory Flow System.

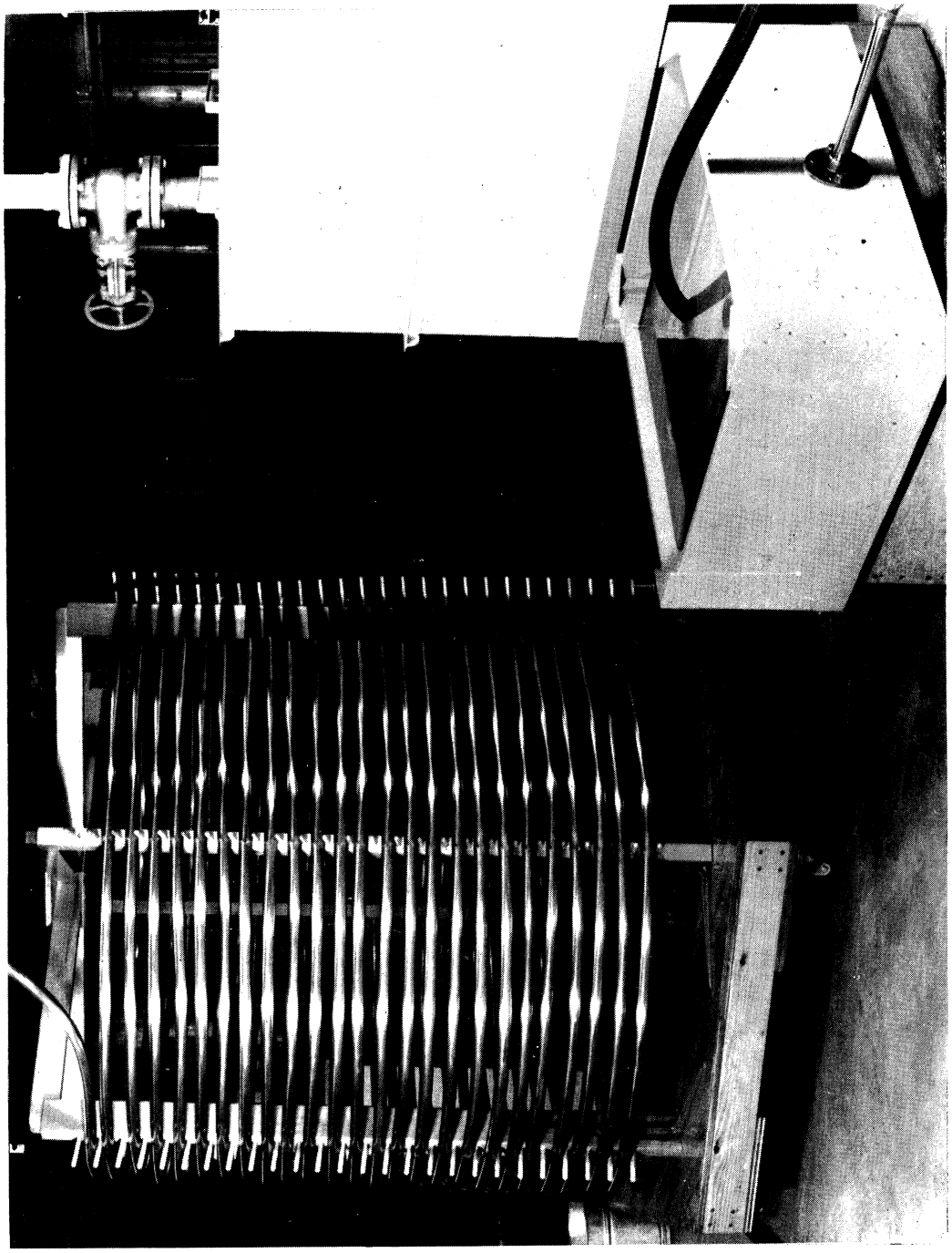

Figure 15. View of Constant-Head Weir Box and Loosely Coiled Copper Pipe on Wooden Frame.

TABLE I

COPPER PIPE PROPERTIES

Segment	Length ft.	Inside Diameter ft.	Wall Thickness ft.	Density lb./ft.^{3}	Modulus of Elasticity lb. ft.^{2} x 10^{10}
Inlet	1.25	.0824	.00532	546	.2448
1	100.00	.0836	.00529	558	.2448
2	100.16	.0831	.00535	558	.2448
3	100.19	.0832	.00529	558	.2448
4	100.13	.0816	.00540	558	.2448
Connector	37.46	.0828	.00528	558	.2448
Total or Average Values	439.19	.0829	.00532	558	.2448

Because the properties of the copper pipe segments were similar with respect to each other, they were treated as one continuous pipe having average characteristics.

The plexiglas pipe was constructed of two short lengths of pipe cemented together to form a continuous tube 8.44 feet in length. Plexiglas flanges were machined and fitted to the ends of the pipe, thereby permitting connection to a similar bronze flange attached to the copper pipe on the one hand, and to another bronze flange attached to the gate valve on the other hand. O-rings inserted between the flanges in machined chamfers provided leak-proof connections. A steel frame was used to hold the pipe firmly in position. Although the pipe could still accommodate radial strains, the frame curtailed axial strains. The cast plastic pipe was assumed to be isotropic. Its properties are listed in the table following:

TABLE II

PLASTIC PIPE PROPERTIES

Length ft.	Inside Diameter ft.	Wall Thickness ft.	Density lb./ft.^{3}	Modulus of Elasticity lb./ft.^{2} x 10^8
8.77	.0828	.0211	73.63	.5112*

*Methyl Methacrylate (acrylic resin) at 26°C.

The steel frame used to secure the plexiglas pipe also served as a mounting for the quick-closing, solenoid-actuated gate valve. Because this frame was designed to permit rotational adjustments about a horizontal axis, the value was positioned so that the axis of rotation passed through the center of the gate opening. However, all investigations undertaken in this study were conducted with the plastic pipe in the horizontal position.

The solenoid-actuated valve was normally in the open position. When actuated by the solenoid the sliding gate was pushed downward until the circular passage in the gate was no longer aligned with the inlet and outlet ports. The time-of-closure was found to vary from less than 20 milliseconds to nearly 60 milliseconds, depending upon the phase position of the AC voltage at the moment the solenoid coil was energized. Clearly, the instantaneous valve closure assumed in the theoretical phase of the study was not achieved in the laboratory. However, because the round-trip travel time of the main pressure wave was in fact equivalent to instantaneous valve closure.

Because the flow system was operated under syphon conditions, the drain hole at the bottom of the valve chamber was submerged in a reservoir of water.

Figures 16 and 17 show the plexiglas pipe, the solenoid-operated gate valve, and the steel supporting frame from two different vantage points. Figure 18 provides a close-up view of the principal test section in the plexiglas pipe, the solenoid-actuated gate valve, and the supporting frame and mounting bracket.

A one-inch inside diameter copper pipe was used to return the flow from the valve to a lower elevation. A heavy-duty, one-inch inside diameter rubber hose connected to this pipe returned the flow to the laboratory sump, thereby completing the flow system.

Instrumentation

Three sets of piezometer rings were attached to the copper pipe system. The first ring was located just beyond the entrance to the pipe system at the weir box; the second was placed immediately ahead of the junction between the copper and the plastic pipes; and the third ring was positioned just beyond the gate valve. A removable, fourth plexiglas piezometer ring (shown hanging from the dual manometer stand in Figure 16) was available for insertion at the junction between the plexiglas pipe and the gate valve. When connected to the appropriate manometers these piezometer rings were used to determine the friction loss characteristics of the flow system.

A Dynisco unbonded strain-gage type transducer was used to determine the transient pressures at the gate valve. This transducer, which was mounted nearly flush with the inside wall of the pipe and

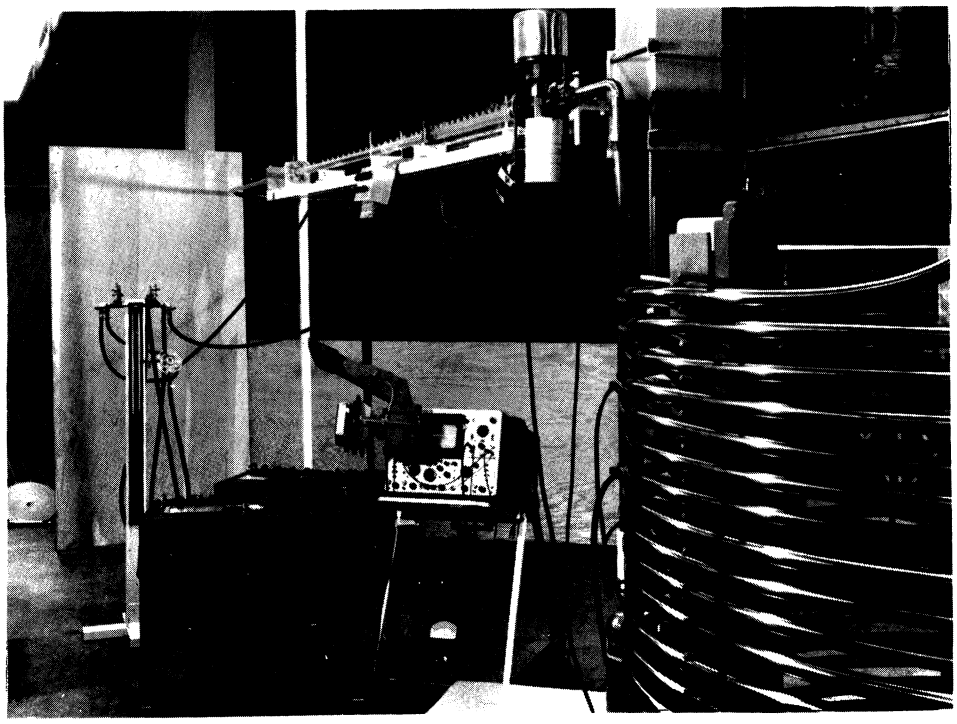

Figure 16. View of Coiled Copper Pipe, Plexiglas Pipe, Solenoid-Operated Gate Valve, and Assorted Instrumentation. Plexiglas Pipe and Gate Valve are Mounted on Steel Frame Clamped to Structural Column.

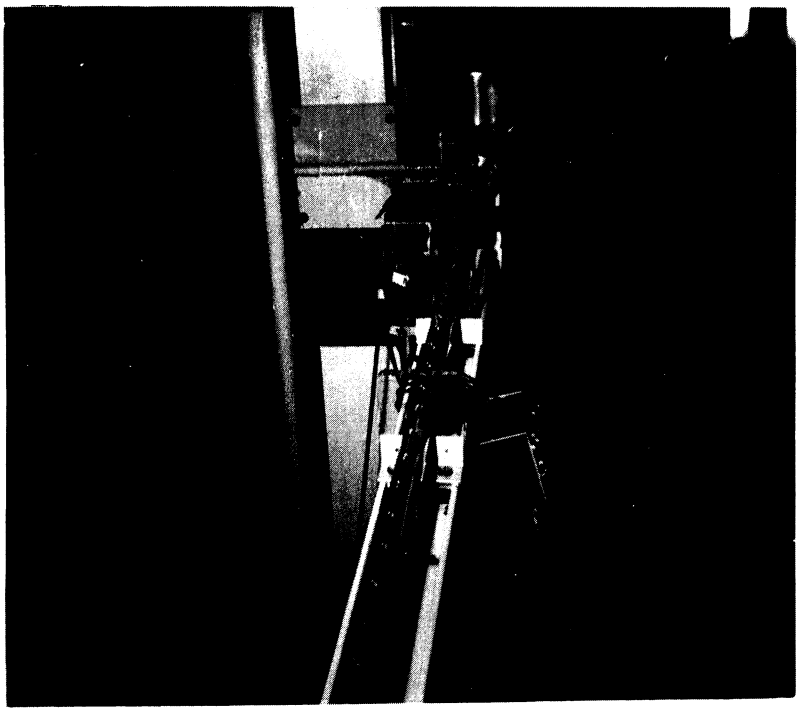

Figure 17. Top View of Plexiglas Pipe and Solenoid Operated Gate Valve.

normal to the longitudinal axis, was temperature compensated throughout its full 0-300 psia pressure sensing range. Its range of frequency response was 0-12,000 cps. The transducer is partially visible on the back side of the pipe in the center of Figure 18. An Ellis BAM-1 bridge amplifier was used not only to supply the input voltage needed to activate the four arms of the Wheatstone bridge circuit in the transducer, but also to amplify the response signal. The output of the amplifier was displayed on a Tektronics Model 565 dual beam oscilloscope equipped with a polaroid camera.

In order to determine the magnitude and shape of the vapor cavities a series of miniature wave gages were very tediously installed throughout the length of the plexiglas pipe. Each gage, consisting of .002-inch diameter nickel-chrome resistance wire threaded in a "W"-like pattern through the walls of the pipe and cemented in place with epoxy resin, could serve as a single leg in a variable conductance Wheatstone bridge circuit. The gages were vertically oriented in a plane normal to the axis of flow. The first gage, located as close to the gate valve as possible, was .342 foot from the near face of the gate while the second gage was .500 foot from the face. The next 17 gages were spaced at 2-inch intervals, the following 16 gages at 3-inch intervals, and the remaining gages at 6-inch intervals. A total of 37 gages were installed in the plexiglas pipe. Figure 19 shows a sample miniature wave gage typical of the gages installed in the plexiglas pipe. Several of the actual gages are visible in Figures 16-18.

Two Sanborn Twin-Viso oscillographs equipped with A.C. amplifiers (2400 cps) were used to activate the gages, amplify the responses, and record the resulting signals. Four identical bridge circuits were provided

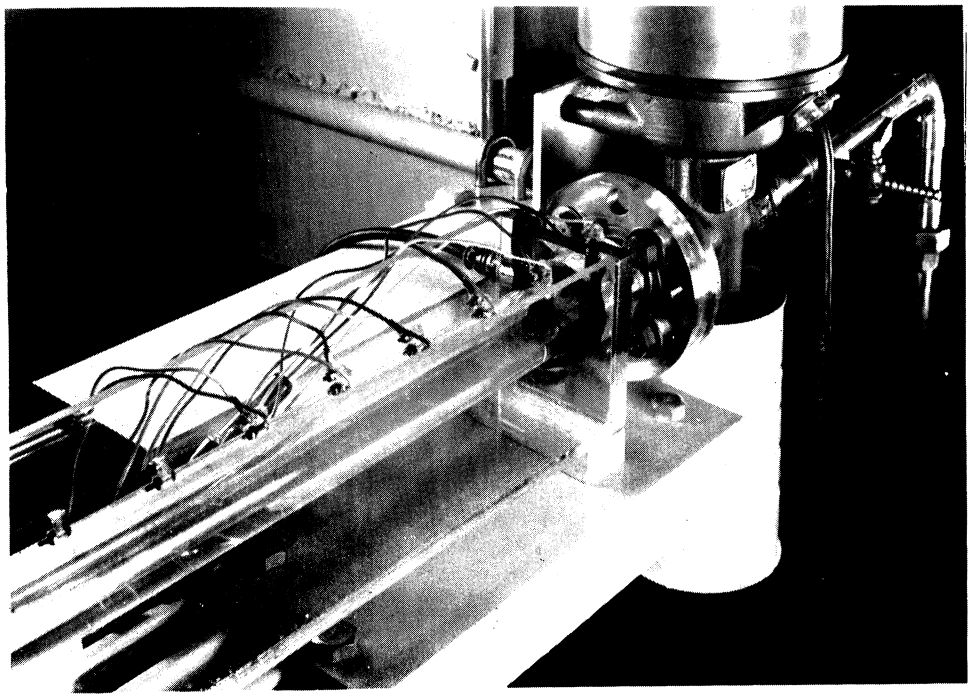

Figure 18. Close-Up View of Principal Test Section Depth Gages and Pressure Transducer Mounted in Plexiglas Pipe.

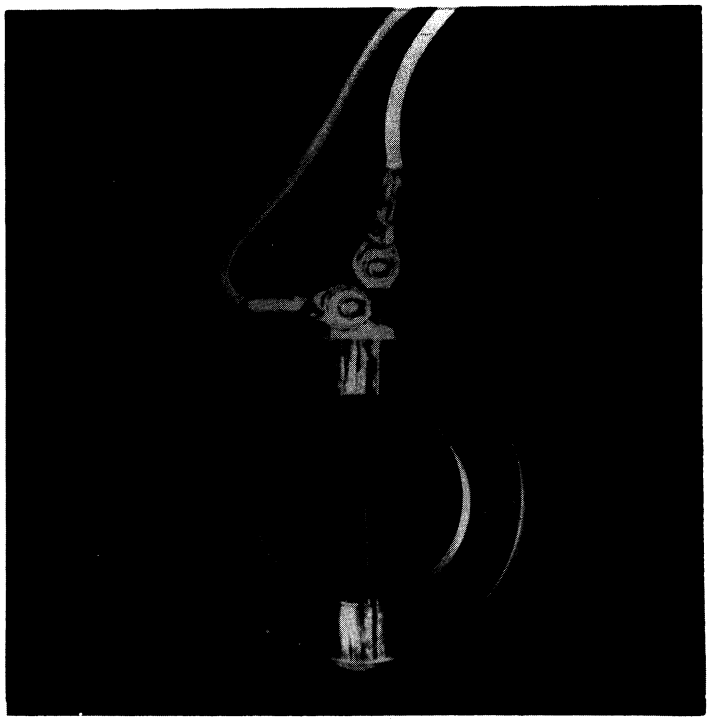

Figure 19. Enlarged View of Sample Depth Gage.

in order that any four gages could be monitered simultaneously. A schematic diagram of the bridge circuit is shown in Figure 20. The two Sanborn units were interconnected and their circuits slightly modified in other ways to eliminate beat frequencies and minimize cross-signal feedback. Figure 21 provides a closeup view of the two oscillograph units, the camera-equipped oscilloscope, and the bridge amplifier unit used in the study.

System Calibration

The unique frictional resistance characteristics of the laboratory flow system were investigated for the full range of anticipated rates of discharge. The head losses in both the plexiglas pipe (pipe segment 1) and the copper pipe (pipe segment 2), were determined for 55 different rates of discharge. Two differential manometers were used to measure the head losses, while weigh-tank observations were used to determine the flow velocities. These data, together with the appropriate kinematic viscosity data, were used to obtain the steady-state, frictional flow-resistance term f, and the associated Reynolds number. Figure 22 is a graphical representation of the typical flow resistance relationships obtained by plotting the respective data versus the associated Reynolds numbers. While the relationships shown in Figure 22 admittedly represent steady state flow resistance characteristics, the flow resistance relationships for transient flow conditions are assumed to be equivalent.

Before undertaking the investigation of the column separation accompanying transient flow in the experimental laboratory apparatus, both the pressure-sensing instrumentation and the wave or depth-sensing

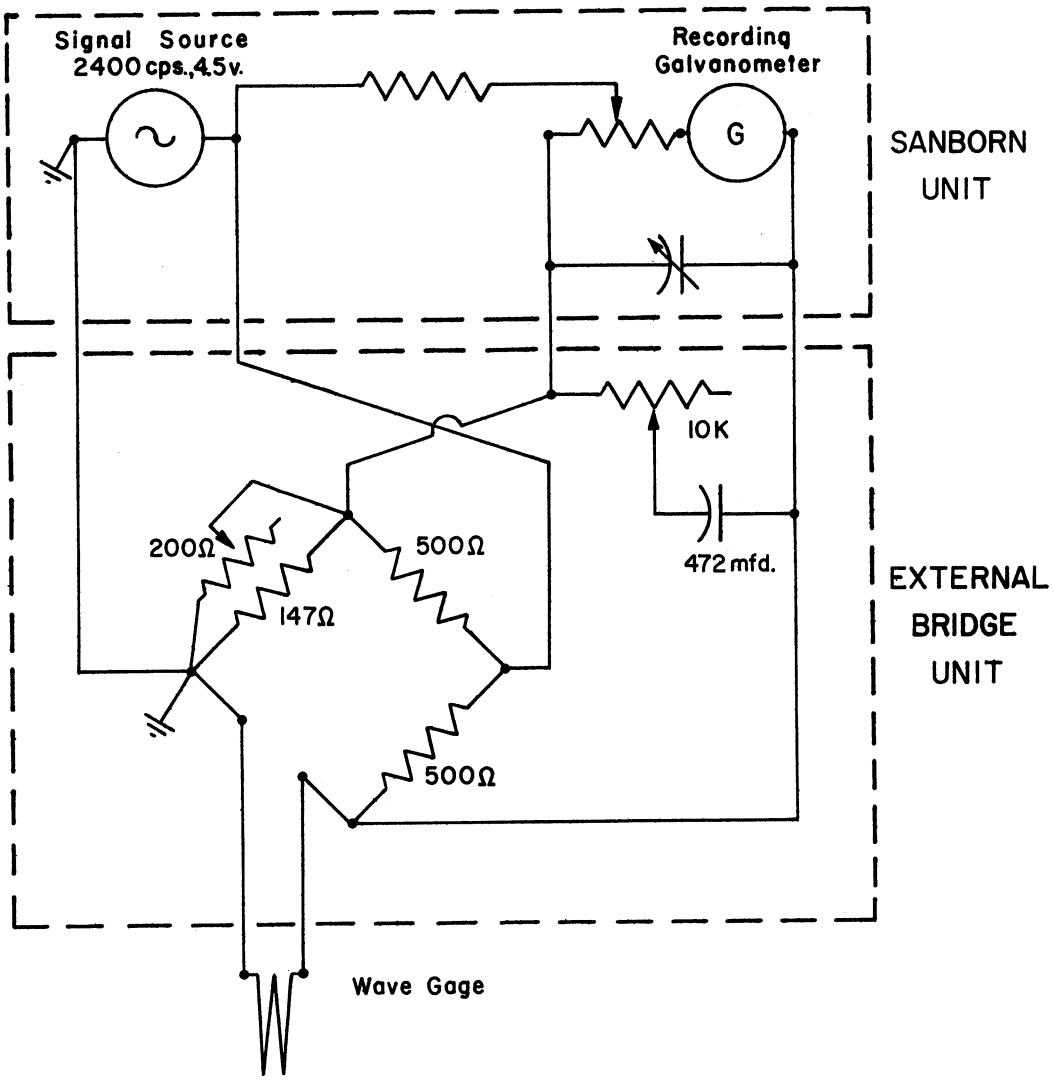

Figure 20. Diagram of Circuit Designed for Use with a Miniture Wave Gage.

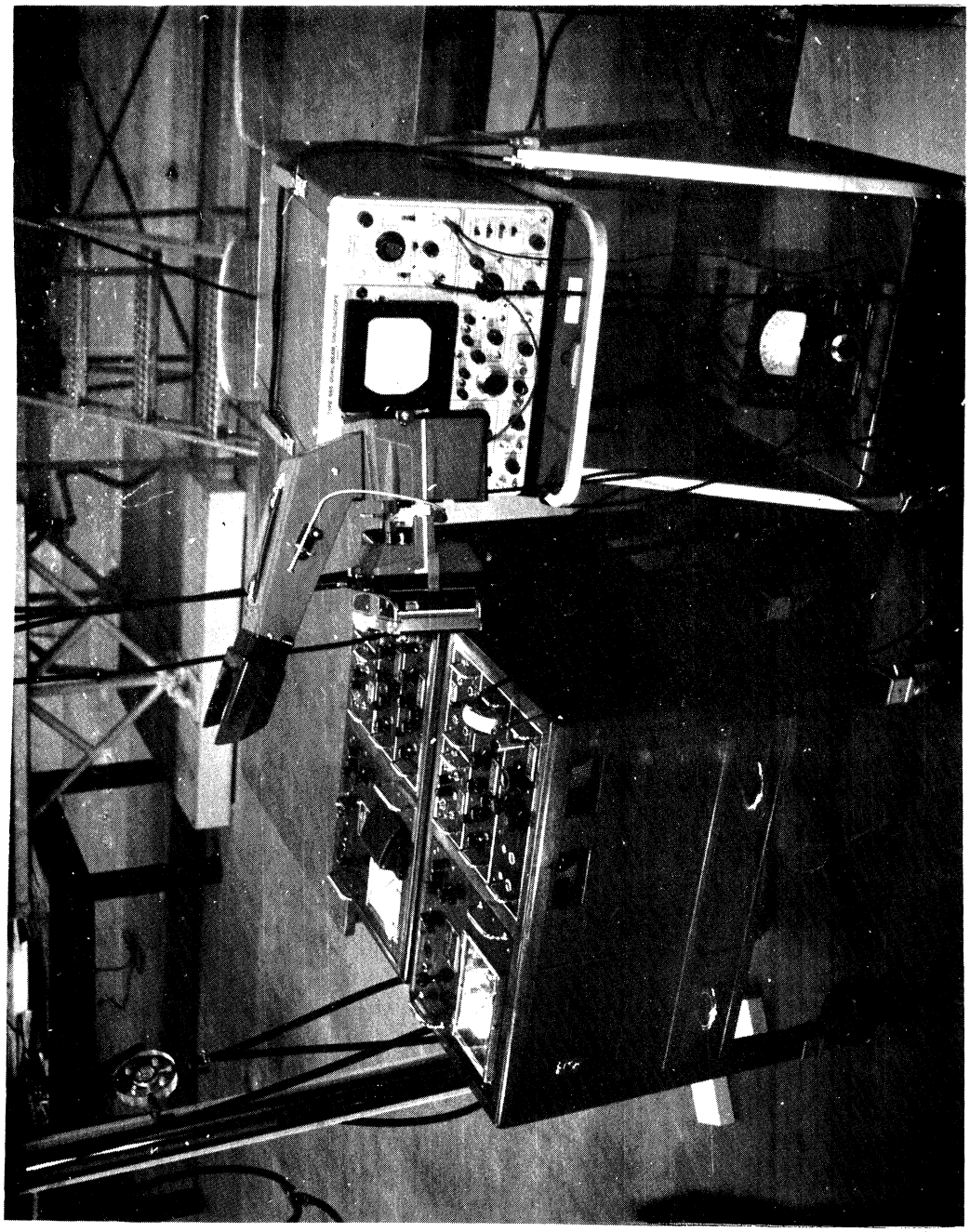

Figure 21. Close-Up View of Dual-Channel Oscillograph Units, Camera Equipped Oscilloscope, and Bridge Amplifier Unit.

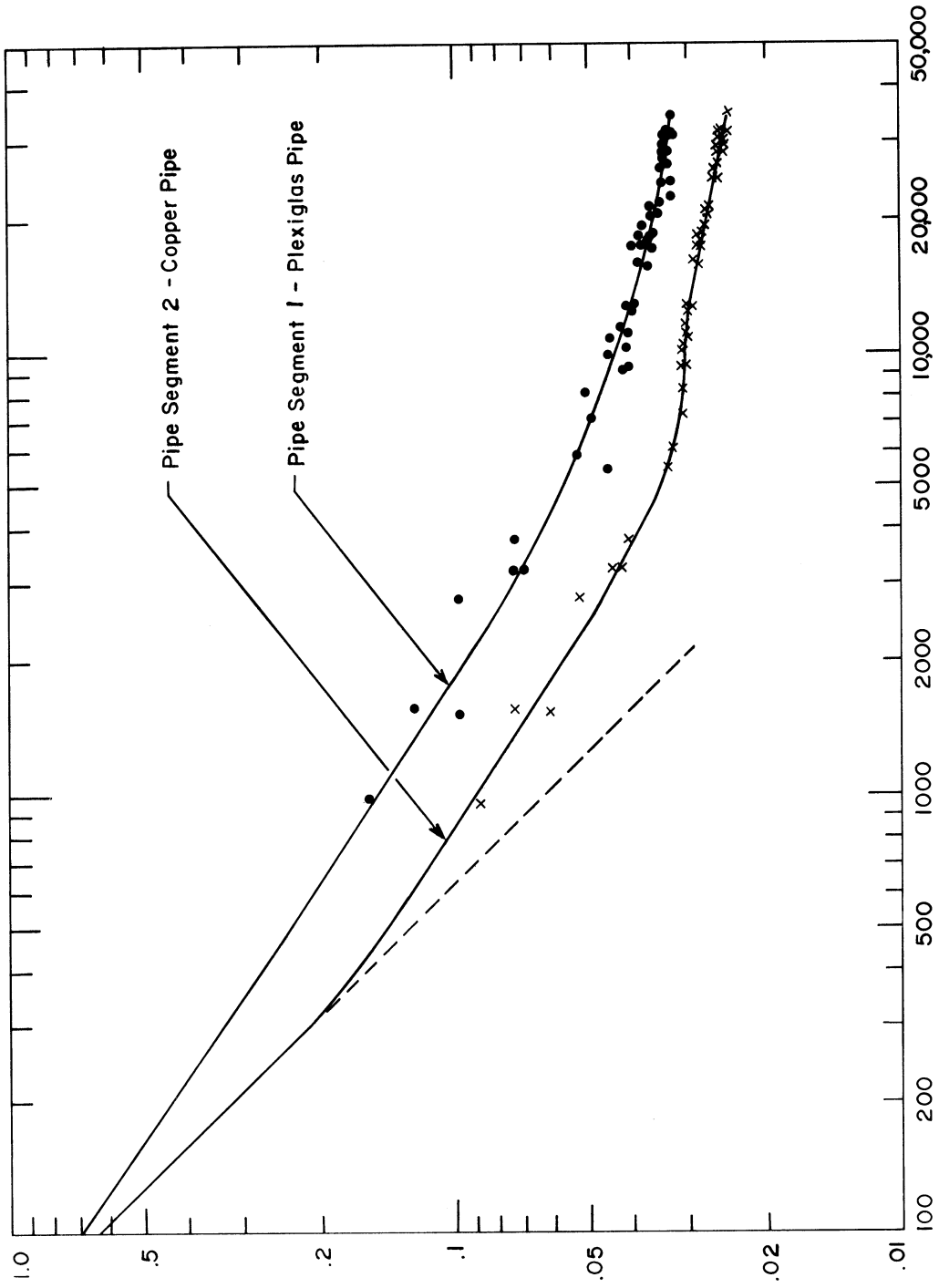

Figure 22. Flow-Resistance Relationships for the Copper and Plexiglas Pipes.

instrumentation had to be thoroughly checked, adjusted, and fully calibrated. In fact, these operations had to be repeated frequently in order to insure that all equipment was functioning properly and that the observed readings were indeed meaningful and accurate.

The pressure transducer was carefully checked for accuracy of full-scale reading using a dead-weight gage tester. Then the proper scaling was established on the Ellis bridge amplifier and on the oscilliscope to give the proper beam deflections on the dual beam cathode ray tube. The dead weight gage tester was used to determine the desired scaling.

Maintenance and calibration of the depth sensing gages proved to be a tedious, complex, and often difficult task. Although these gages were all of similar design, each one had unique calibration characteristics which had to be taken into account. Calibration of these gages consisted of establishing (or reestablishing) the zero flow or dry pipe adjustment of the appropriate oscillograph channels. Next the full-flow reading was used to adjust the various oscillograph channels for proper scaling with a particular gage. Another reading had to be taken to compensate for the pressure condition in the pipe. This reading was subsequently used as an adjustment applied to the recorded values during appropriate periods in time.

The time required to adjust, calibrate, and stabilize the operation of the wave gages ranged from one or two hours to as much as a day or longer. Fortunately, once proper operation was achieved only minor adjustments were required between successive column separation experiments in a sequence of investigations.

Experimental Procedures

Actual column-separation experiments could be undertaken only after all electronic equipment had operated sufficiently long to insure its stability and after all instrument calibration had been successfully accomplished. The first step in an experiment was to prime the pipe system and thereby establish syphon flow. The priming operation was done by temporarily attaching a hose to the inlet of the system in the weir box. Water drawn under pressure from the laboratory constant head tank was used for priming and for flushing out entrapped air. All piezometers were bled to eliminate air which may have become trapped in the piezometer rings. Flow in the system was regulated by means of a throttle valve in the sump return pipe. The steady-state discharge was determined by using a stop watch and a scale to time and weigh, respectively, several sampled quantities of water passing through the system. Water temperature readings and mercury barometer readings were recorded at frequent intervals throughout an experimental period.

To initiate transient flow and the subsequent column separation, the recording oscillographs were started and the shutter of the polaroid camera attached to the oscilloscope was opened immediately prior to the instant the solenoid valve was switched shut. When the valve closed, the self-triggering, beam-sweep circuits in the dual-beam oscilloscope caused the trace of the pressure wave sensed by the transducer at the gate valve to be recorded on film. The upper beam was used to record the individual pressure peaks superimposed, one upon the other, using an expanded time scale. The lower beam recorded the entire sequence of pressure peaks separated by periods of column separation during a 5-second sweep interval. The trace of transient pressures observed at the gate valve and

shown in Figure 23 for laboratory run No. 19 is typical of the data obtained from the pressure transducer. In this figure a major division in the vertical direction is equivalent to 55 psia. A major division in the horizontal direction on the upper scale is equivalent to .05 second; on the lower scale, .5 second.

Meanwhile, the oscillographs recorded the depth of flow at selected points within the travel range of the cavitation void. Figure 24 shows a typical set of data obtained simultaneously on one of the twin-channel, strip-chart oscillographs during laboratory run No. 33. The upper trace represents the depth of flow observed at miniature wave-gage No. 1; the lower trace, the transient pressures at the gate valve. The trace of the transient pressure was frequently recorded on one of the four oscillograph channels to assure the simultaneity of time base for all recording media. One-second tick marks are visible along the lower edge of the chart in Figure 23; the major chart divisions are 5mm., the minor divisions are 1 mm. so that the chart speed was 100 mm. per second. Simultaneous strip-chart traces representing the depth of flow at two other wave gages were recorded on the second, twin-channel oscillograph.

On certain laboratory runs photographs of the cavitation void were taken.

Once column separation had ceased and the transient pressure wave had diminished due to friction, the solenoid valve was opened and the recorded data was removed from the recording instruments and marked for subsequent identification. The system could then be reinitialized

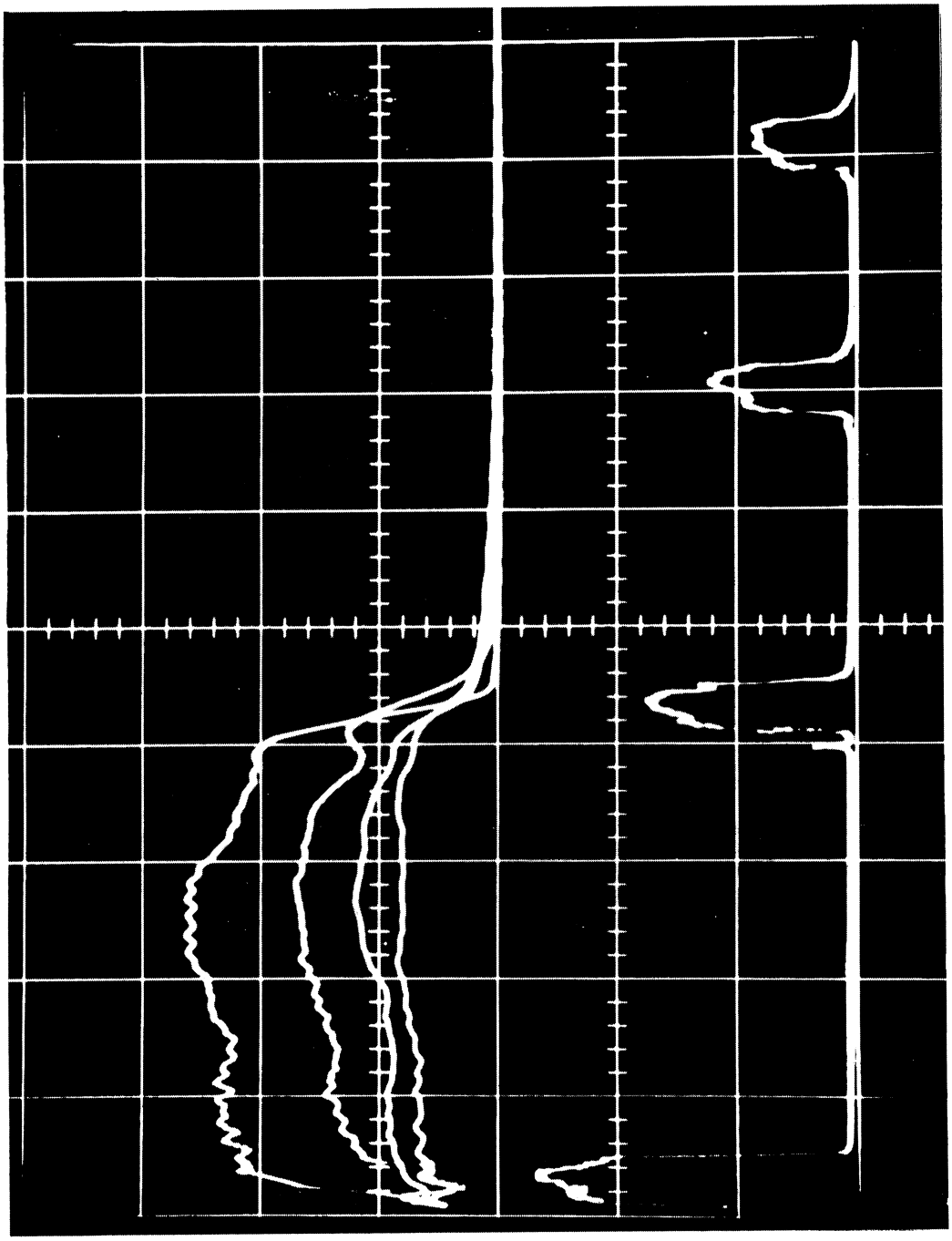

Figure 23. Transient Pressures, Photographically Recorded from the Oscilloscope Cathod-Ray Tube During Laboratory Run Number 19, are Typical of the Experimental Pressures Observed at the Gate Valve.

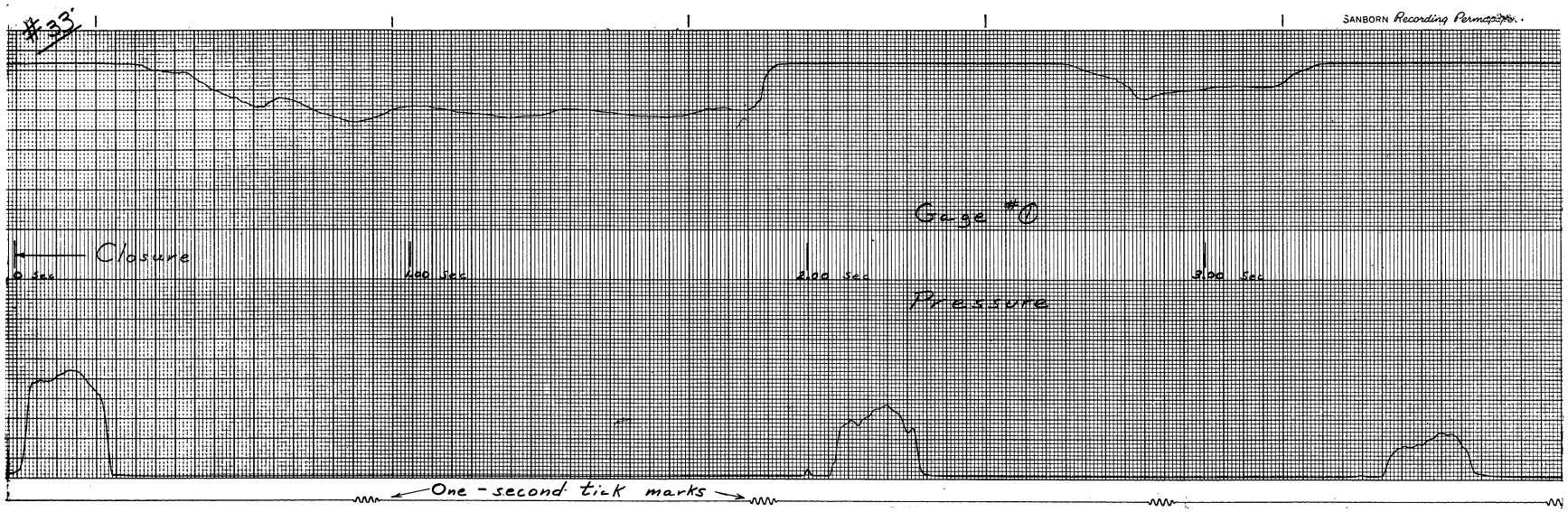

Figure 24. The Time-Dependent, Oscillograph Data Trace Shown at Top is Typical of the Free-Surface Flow Depths Observed at Gage Number 1 During Periods of Column Separation in the Pipe. The Data Trace Shown at Bottom Represents the Simultaneously Observed Transient Pressure at the Nearby Gate Valve. Traces Were Recorded During Laboratory Run Number 33. Depth-of-Flow Data Traces, Not Shown But Similar to the Top Trace, Were Simultaneously Recorded for Two Other Gages on a Second Oscillograph.

and made ready for the next experimental run. It was found essential to recheck all instrument calibrations before starting each new laboratory experimental run.

The experimental results are presented in the next chapter and compared with the theoretical results obtained from computer simulation for the same physical conditions.

CHAPTER VI

COMPARISON AND DISCUSSION OF EXPERIMENTAL AND THEORETICAL RESULTS

The study of column separation accompanying the transient flow of liquids in pipes culminates in this chapter with comparisons of the laboratory-observed, experimental results and the computer-simulated, theoretical results derived from the mathematical model. The ability to throttle the syphon-flow velocity and to vary the elevation of the solenoid-operated valve throughout a range of approximately 26 feet, as well as intrinsic fluctuations in the atmospheric pressure and in the water temperature offered a limitless combination of experimental conditions for laboratory investigation. However, practical constraints on the time which could be profitably expended analyzing laboratory data and economic sanctions on the use of computer time, limited this study to the investigation of only a few selected conditions. These conditions are briefly presented in the first section. A detailed comparison of the experimental and theoretical results obtained for one particular set of investigated conditions is presented in the subsequent section. Analysis and discussion of the similarities and dissimilarities between the theoretical and experimental pressure rises are followed by a similar appraisal of the theoretical and experimental column-separation voids. The significance of these findings is discussed in the final section.

Conditions Investigated

Experimental data were gathered for three distinct sets of laboratory conditions. These conditions differed, one from another, because of differences in the elevation of the solenoid-operated gate valve, differences in the initial steady-state rate of flow, or because of both.

However, minor changes in atmospheric pressure and in water temperature, along with slight fluctuations in the initial rate of flow resulted in subset conditions within two of the principal sets of conditions. Table III is a summary of the 34 data runs considered in the experimental phase of the study. The grouping of the various data runs according to laboratory conditions is tabulated below:

(a) Group I: Runs No. 1-10

Valve Elevation (HEL) = 27.980 feet

Location (Loc 1) = 39.00 feet

Initial Steady-state Discharge (Q) $\cong$ -0.0107 cubic feet per second

(b) Group II: Runs No. 11-25, 31-34

Valve Elevation (HEL) = 34.719 feet

Location (Loc 1) = 18.00 feet

Initial Steady-State Discharge (Q) $\cong$ -0.0107 cubic feet per second

(c) Group III: Runs No. 26-30

Valve Elevation (HEL) = 37.719 feet

Location (Loc 1) = 18.00 feet

Initial Steady-State Discharge (Q) $\cong$ -0.0078 cubic feet per second

These same parameters, together with other parameters describing the nonvariable experimental conditions, were used as input data to the computer program. Computer simulations were then carried out for the three laboratory conditions.

TABLE III

SUMMARY OF EXPERIMENTAL RUNS

Run No.	Date 1964	Configuration HEL ft	Configuration LOCI ft	Water Temp. Deg. F	Atmos. Pressure ft	Rho ρ Slugs/ft^3	Nu ft^2/sec 10^{-5}	Q ft^3/sec	Oscilloscope Data	Oscillograph Data Gage	Gage	Gage	Photo	Max. Extent feet	Rise Time 2nd sec	Rise Time 3rd sec
1	3-3	27.980	39.00	72°	32.683	1.936	1.033	-.01077	Yes	1	2	3	No	-	1.81	3.12
2	3-3	27.980	39.00	72°	32.683	1.936	1.033	-.01077	Yes	1	2	3	No	1.06	1.79	3.08
3	3-3	27.980	39.00	72°	32.682	1.936	1.033	-.01077	Yes	1	2	3	No	1.03	1.76	3.04
4	3-3	27.980	39.00	72°	32.681	1.936	1.033	-.01077	Yes	1	2	3	No	1.01	1.76	3.03
5	3-3	27.980	39.00	72°	32.680	1.936	1.033	-.01077	Yes	1	2	3	No	.96	1.72	2.88
6	3-3	27.980	39.00	72°	32.680	1.936	1.033	-.01077	Yes	1	2	3	No	.92	1.68	2.83
7	3-4	27.980	39.00	75°	32.528	1.935	.995	-.01058	Yes	1	2	3	No	.99	1.76	2.99
8	3-4	27.980	39.00	75°	32.528	1.935	.995	-.01058	Yes	1	2	3	No	-	1.69	2.97
9	3-4	27.980	39.00	75°	32.528	1.935	.995	-.01058	Yes	1	2	3	No	.96	1.69	2.83
10	3-4	27.980	39.00	75°	32.528	1.935	.995	-.01058	Yes	1	2	3	No	.90	1.68	2.78
11	3-7	34.719	18.00	75°	33.116	1.935	.995	-.01073	Yes	1	4	5	Yes	1.16	1.98	3.34
12	3-7	34.719	18.00	75°	33.116	1.935	.995	-.01073	Yes	1	4	3	No	1.14	2.00	3.41
13	3-7	34.719	18.00	75°	33.126	1.935	.995	-.01073	Yes	1	4	3	No	1.11	1.95	3.22
14	3-7	34.719	18.00	75°	33.134	1.935	.995	-.01073	Yes	1	4	3	Yes	1.09	1.91	3.20
15	3-7	34.719	18.00	75°	33.152	1.935	.995	-.01073	Yes	1	4	3	No	1.08	1.91	3.18
16	3-7	34.719	18.00	75°	33.170	1.935	.995	-.01073	Yes	1	3	4	No	1.18	1.96	3.27
17	3-7	34.719	18.00	75°	33.188	1.935	.995	-.01073	Yes	1	3	4	Yes	1.22	1.92	3.18
18	3-7	34.719	18.00	75°	33.206	1.935	.995	-.01073	Yes	1	2	4	No	1.23	1.91	3.17
19	3-7	34.719	18.00	75°	33.224	1.935	.995	-.01073	Yes	1	2	4	Yes	1.26	2.07	3.45
20	3-7	34.719	18.00	75°	33.239	1.935	.995	-.01073	Yes	1	2	4	No	1.13	1.90	3.12
21	3-7	34.719	18.00	75°	33.258	1.935	.995	-.01073	Yes	1	2	4	No	-	1.87	3.06
22	3-10	34.719	18.00	72°	32.421	1.936	1.033	-.01054	No	1	2	4	No	1.13	2.04	3.37
23	3-10	34.719	18.00	72°	32.421	1.936	1.033	-.01054	Yes	1	2	4	No	1.21	2.05	3.40
24	3-10	34.719	18.00	72°	32.421	1.936	1.033	-.01054	Yes	1	2	4	No	1.25	2.05	3.40
25	3-10	34.719	18.00	72°	32.421	1.936	1.033	-.01054	Yes	1	2	4	No	1.19	2.11	3.32
26	3-10	34.719	18.00	72°	32.421	1.936	1.033	-.00777	Yes	1	2	4	No	-	1.64	2.75
27	3-10	34.719	18.00	72°	32.421	1.936	1.033	-.00777	Yes	1	2	3	Yes	-	1.63	2.75
28	3-10	34.719	18.00	72°	32.421	1.936	1.033	-.00777	Yes	1	2	3	No	.82	1.63	2.73
29	3-10	34.719	18.00	72°	32.421	1.936	1.033	-.00777	Yes	1	2	4	No	.88	1.66	2.79
30	3-10	34.719	18.00	72°	32.421	1.936	1.033	-.00777	Yes	1	2	4	No	.78	1.62	2.72
31	3-10	34.719	18.00	72°	32.421	1.936	1.033	-.01054	Yes	1	5	3	No	1.28	2.05	3.43
32	3-10	34.719	18.00	72°	32.421	1.936	1.033	-.01054	Yes	1	5	4	No	1.24	2.03	3.42
33	3-10	34.719	18.00	72°	32.421	1.936	1.033	-.01054	Yes	1	5	4	Yes	1.22	2.05	3.42
34	3-10	34.719	18.00	72°	32.421	1.936	1.033	-.01054	Yes	1	5	4	Yes	1.18	1.88	2.99

Comparison of Results

In the theoretical analysis presented in Chapter II, the assumption was made that the pipe flow ahead of the void created by column separation would continue to be full-pipe flow. That this assumption is, in fact, not valid became apparent rather early in the experimental phase of the study. While the free-surface, vapor-filled, column-separation void formed as anticipated, small gaseous cavities--bubbles--were observed to occur ahead of the void and throughout the remaining length of the plexiglas pipe. Moreover, with continued propagation of the low-pressure wave toward the constant head reservoir, similar bubbles were heard to occur throughout most of the length of the copper pipe. With the iminent collapse of the column-separation void and with the subsequent creation of a new high-pressure wave propagating toward the reservoir, the cavitation bubbles were observed to diminish, first, and then, to disappear completely (or almost completely), respectively.

The occurrence of vapor-cavity bubbles ahead of the void has a significant bearing on all aspects of the transient-flow, column-separation phenomena. This significance will become fully evident in the comparisons and detailed discussion which follow.

Two experimental runs, Numbers 25 and 34, were selected from the laboratory data in Group II for detailed comparison with the corresponding computer-simulated results. These runs were considered to be entirely representative of the other experimental runs comprising Group II.

Pressure Rises

Figure 25 presents a time comparison of the transient, absolute pressures occurring at the gate valve as derived from the mathematical

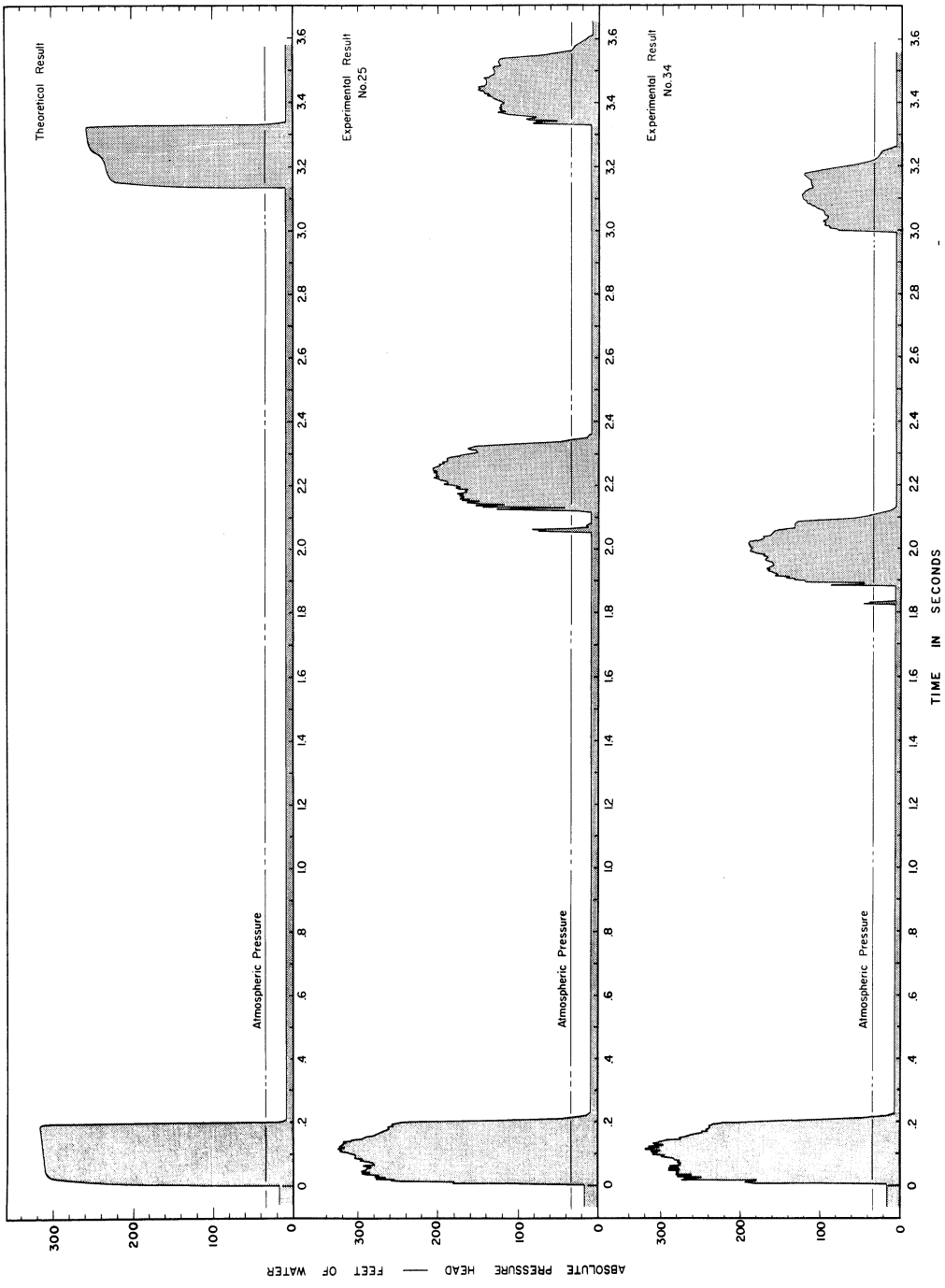

Figure 25. Comparison of the Computer-Simulated, Transient Pressures with the Experimentally Determined Pressures Observed at the Gate Valve During Laboratory Runs Numbers 25 and 34.

model and from laboratory measurements (experimental runs Numbers 25 and 34). Time is measured from the instant the gate valve was closed. For each of the three examples shown, column separation occurs at the valve during the time intervals between the successive pressure rises. Figures 26 and 27 provide detailed overlay comparisons of the computer-simulated and experimentally-determined initial pressure rises and second pressure rises, respectively. Figures 28 and 29 are reproductions of the respective oscilloscope photographs on which the absolute pressure-head data for runs Numbers 25 and 34 were recorded. The numerical data used to plot the experimental results of Figures 25, 26, and 27 are tabulated in Appendix III; many of the data used in plotting the theoretical results are contained in Appendix IV.

Comparative study of Figures 25-27 discloses several factors of note. Principal among these factors are the following:

(a) In broad terms the overall appearances of the three pressure diagrams shown in Figure 25 are similar; abrupt pressure rises separate intervals of subatmospheric pressure during which time column separation occurs.

(b) Despite some minor pressure fluctuations and local pressure differences evident in the experimental results, the three <u>initial</u> pressure rises closely resemble each other in time of occurrence, as well as in shape, duration, and magnitude of the pressure rise.

(c) The experimental <u>second</u> pressure rises, while manifesting the same minor pressure fluctuations and local pressure differences noted in the initial experimental rises, compare favorably in shape and duration with the corresponding

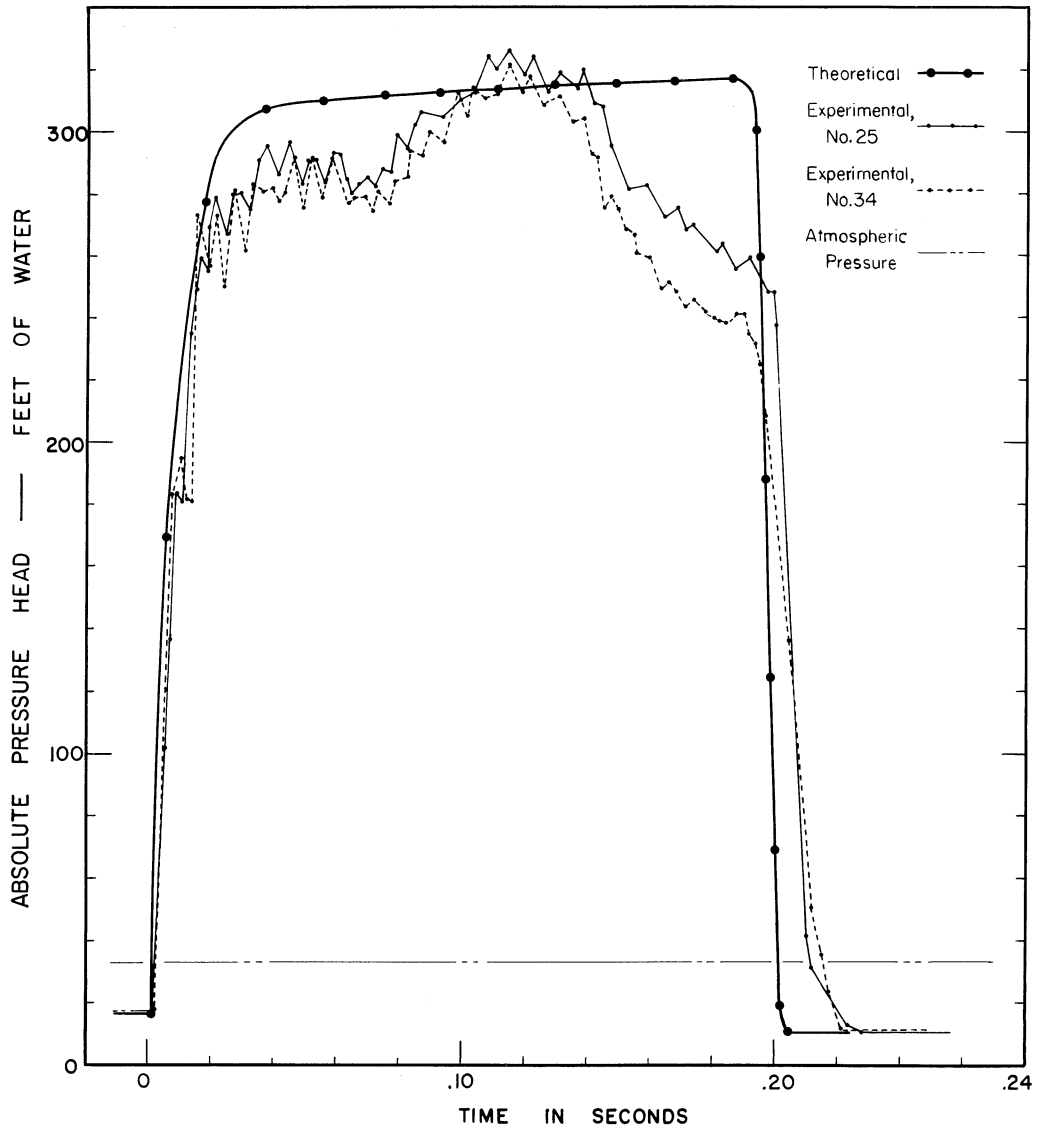

Figure 26. Detailed Comparison of the Computer-Simulated Initial Pressure Rise with the Corresponding Experimentally-Determined Initial Pressure Rises for Laboratory Runs Numbers 25 and 34.

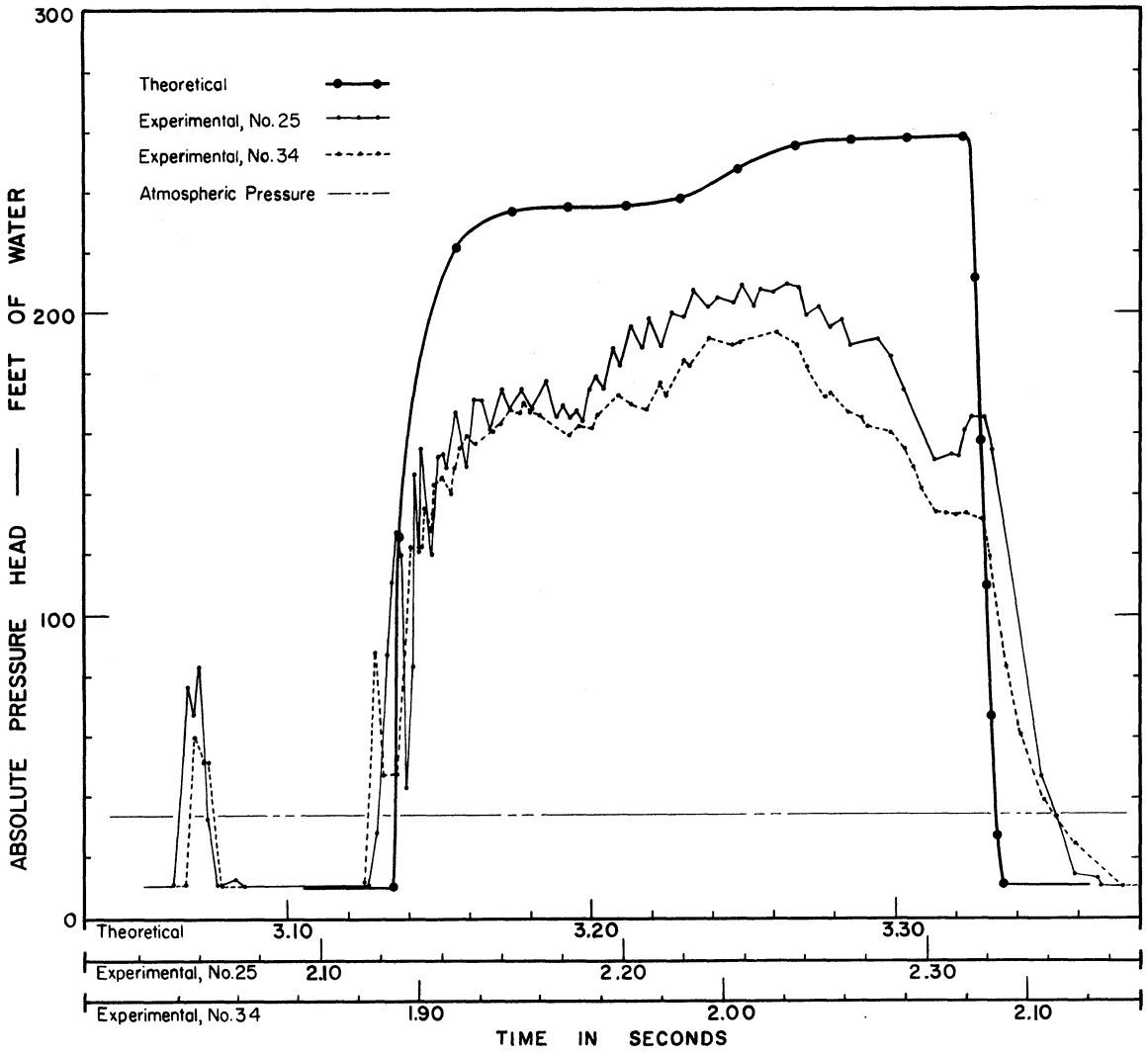

Figure 27. Detailed Comparison of the Computer-Simulated Second Pressure Rise with the Corresponding Experimentally-Determined Second Pressure Rises for Laboratory Runs Numbers 25 and 34.

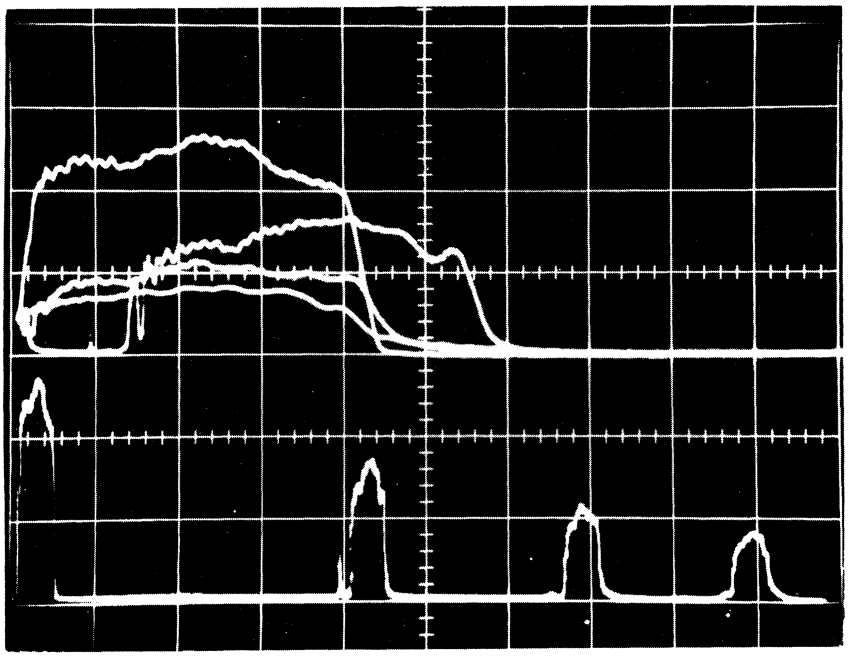

Figure 28. Transient Pressures Observed at Gate Valve During Laboratory Run Number 25.

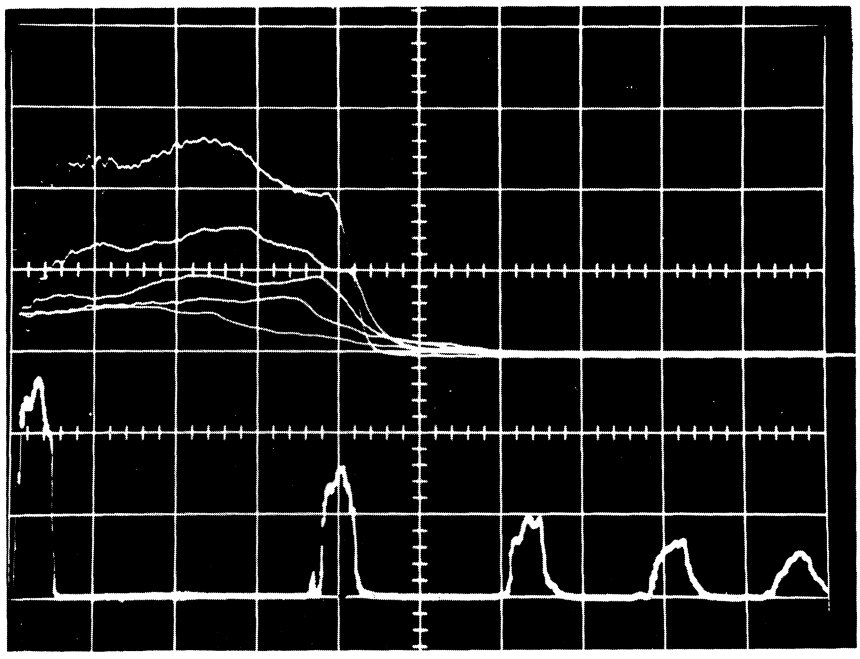

Figure 29. Transient Pressures Observed at Gate Valve During Laboratory Run Number 34.

theoretical pressure rise. However, the magnitudes of the experimental pressure rises are appreciably less than is the magnitude of the theoretically-determined rise.

(d) The recurrence intervals between successive, experimental pressure rises are of appreciably less duration (35-40 percent less) than are the corresponding intervals determined theoretically. (The third theoretical pressure rise, although not shown in Figure 25, was determined to occur beginning at approximately 5.09 seconds after valve closure.)

(e) Appreciable differences occur between the experimental data of laboratory runs Numbers 25 and 34 with regard to the magnitudes of the pressure rises and the duration of the recurrence intervals. Yet, both runs were made ostensively under the same laboratory conditions.

(f) Minor pressure fluctuations appear superimposed on all of the experimental pressure rises. These fluctuations have an apparent duration ranging from 0.0068 to 0.0072 seconds.

(g) Although the duration of both the experimentally and theoretically determined initial pressure rises is very close to 0.2 seconds, a slight tendency toward increased duration appears to develop in the second and subsequent experimental rises. This tendency appears to accompany the deterioration in the abruptness with which the pressure rises collapse.

Among the factors listed above two very significant findings are apparent. One is the considerably shorter duration of the experimental, pressure-rise recurrence interval as compared with the duration of the

theoretically-predicted interval. The second is the more rapid rate at which the magnitudes of the second and all successive pressure rises diminish, again as compared with the theoretical findings. Without even comparing the experimentally and theoretically-determined column-separation voids, it is apparent that the duration of these voids must also be considerably shorter than anticipated from theory. It is probable that the extent of their travel will prove to be similarly reduced.

Taken together the two complementary findings are strong evidence suggesting that during periods of column separation the rate of energy dissipation which occurs in the flow ahead of the void is much higher than anticipated. The obvious question is, "why?" There are several conditions which lead one to believe that a higher energy-dissipation rate could be a direct outgrowth of the "bubble" or "plug" flows taking place in the pipe ahead of the column-separation void. However, a thorough discussion of these circumstances is deferred to a subsequent section.

The laboratory flow system was designed to minimize sources of potential disturbance to pressure wave propagation. The intent, of course, was to assure a clean, uncluttered wave form. It was for this reason that syphon flow was preferred over flow induced by a turbine pump located at the outlet of the system. Nevertheless, not all disturbance-producing elements could be eliminated. Using an expression for the round-trip time-of-travel of a pressure wave in fully confined flow, namely, the expression $t_t = 2\ L_t/a_1$, one finds that the distance, L_t, from the transducer to a disturbance having a propagation and return interval, t_t, of 0.0066 to 0.0072 seconds ranges from 8.1 to 8.9 feet. The term a_1 represents the celerity of propagation of a pressure disturbance in the

plexiglas pipe. This places the source of the disturbance at or just beyond the junction between the copper and plexiglas pipes. The superimposed, minor, pressure fluctuations appearing on the experimental pressure-rise data are believed to be caused by pressure reflections from the small annular chamber of the piezometer ring attached to the copper pipe and situated 0.3 foot from the pipe junction (8.7 feet from the pressure transducer).

Column-Separation Voids

Figure 30 presents a modified isometric diagram showing the absolute pressures at the gate valve, as well as the column-separation void profiles at five successive distances measured from the valve, all with respect to time. The data on this diagram were derived entirely from the mathematical model by digital computer simulation. Figures 31 and 32 are the companion diagrams presenting the corresponding experimentally-derived data from laboratory runs Number 25 and Number 34, respectively. In each of the diagrams the depth of flow, z, in the pipe is measured on the vertical plane passing through the axis of pipe and normal to the bottom inner pipe surface. Figure 33 presents a more detailed comparison of the superimposed depth profiles for both the experimentally-determined and theoretically-determined voids with respect to time.

In Figures 30-33, the column-separation voids are compared on the basis of profiles in the $z - t$ plane at a particular location, x. The voids can also be studied as phenomena occurring in the $x - z$ plane at a selected time t. Figures 34 and 35 present time-sequence

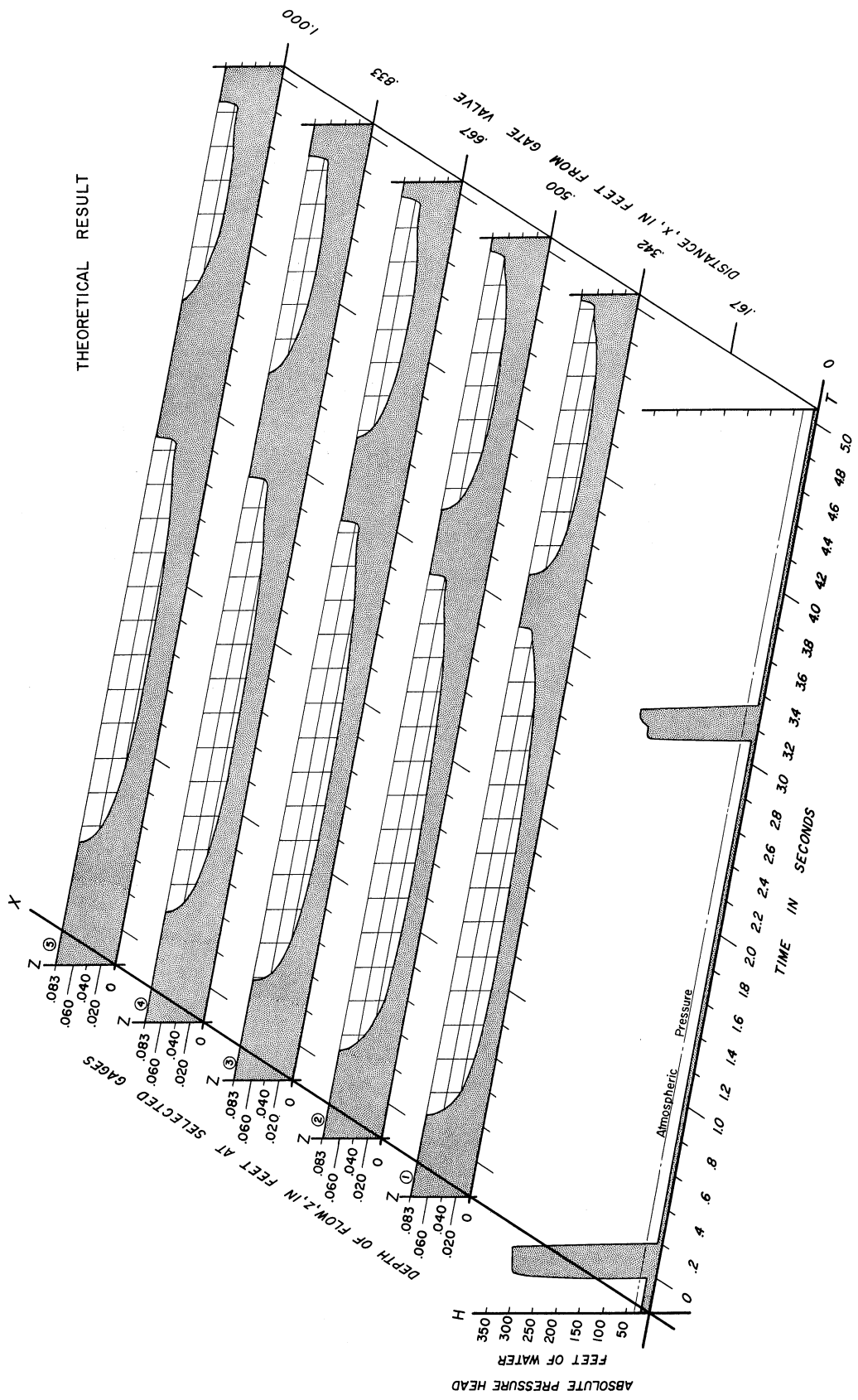

Figure 30. An Isometric Representation of the Computer-Simulated Transient Pressures at the Gate Valve and Concurrent Free-Surface Profiles at Selected Distances from the Gate Valve as Determined from Theoretical Considerations.

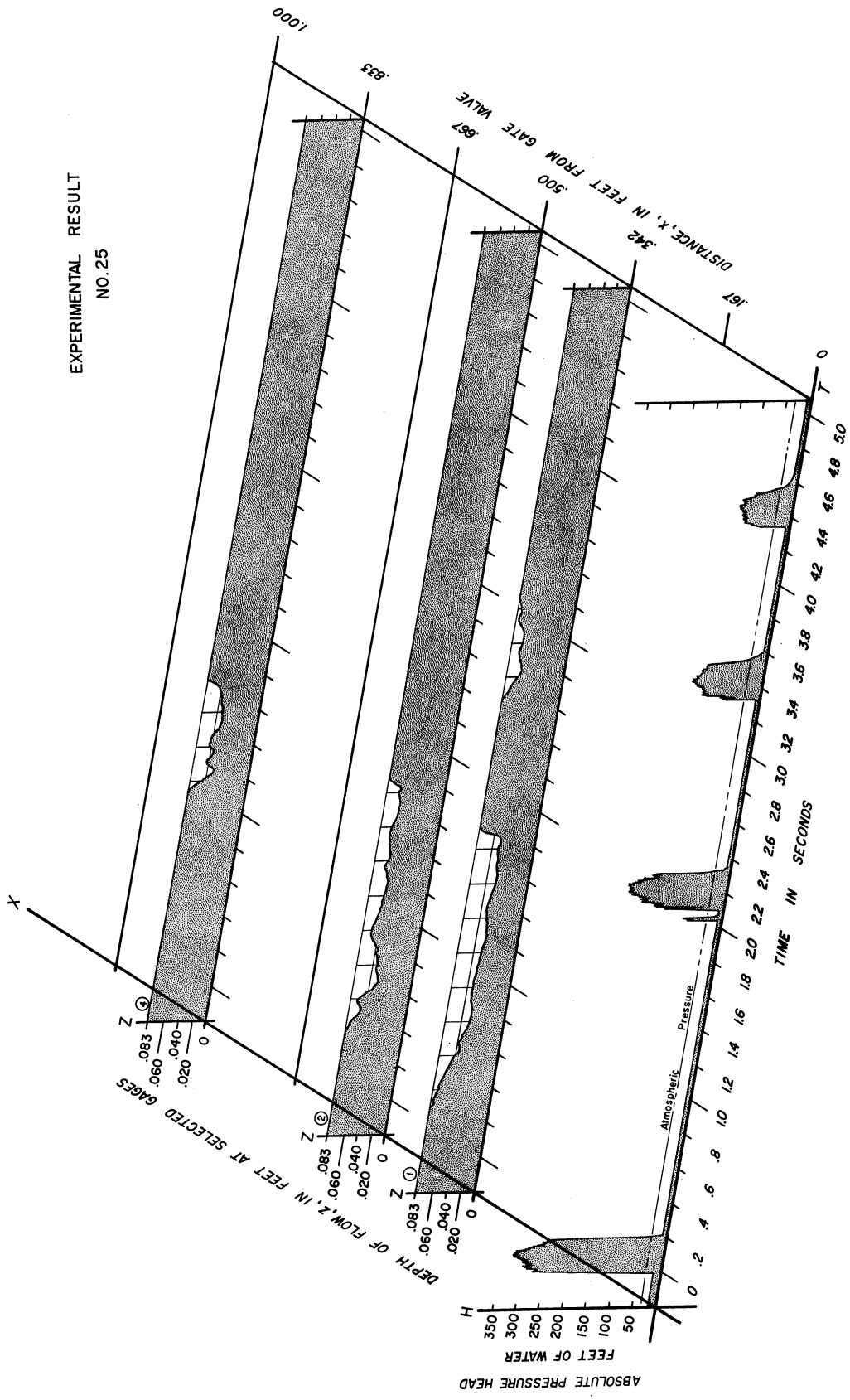

Figure 31. An Isometric Representation of the Experimentally-Determined Transient Pressures at the Gate Valve and Concurrent Free-Surface Profiles at Selected Distances from the Gate Valve as Observed During Laboratory Run Number 25.

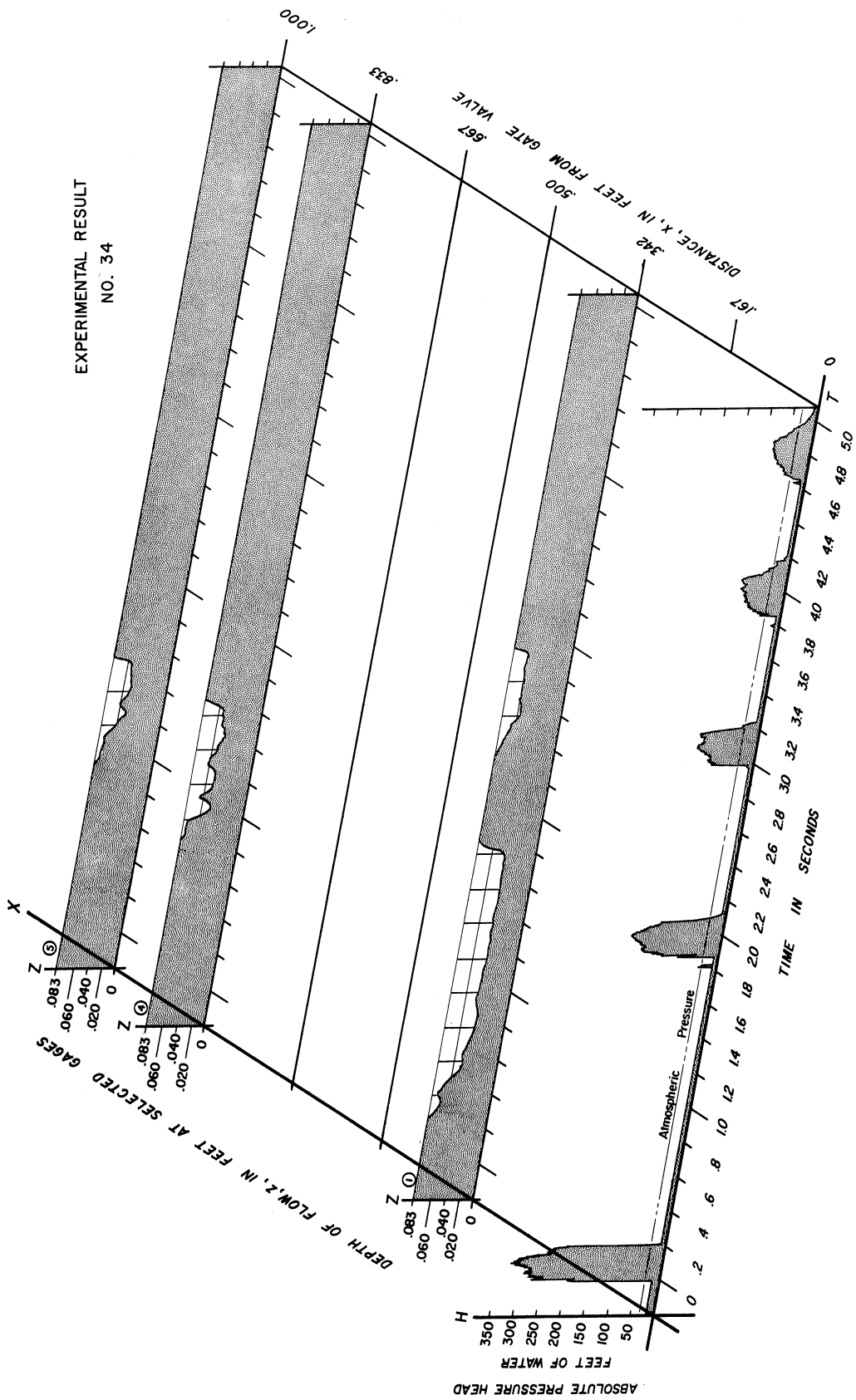

Figure 32. **An Isometric Representation of the Experimentally-Determined Transient Pressures at the Gate Valve and Concurrent Free-Surface Profiles at Selected Distances from the Gate Valve Due to Column Separation During Laboratory Run Number 34.**

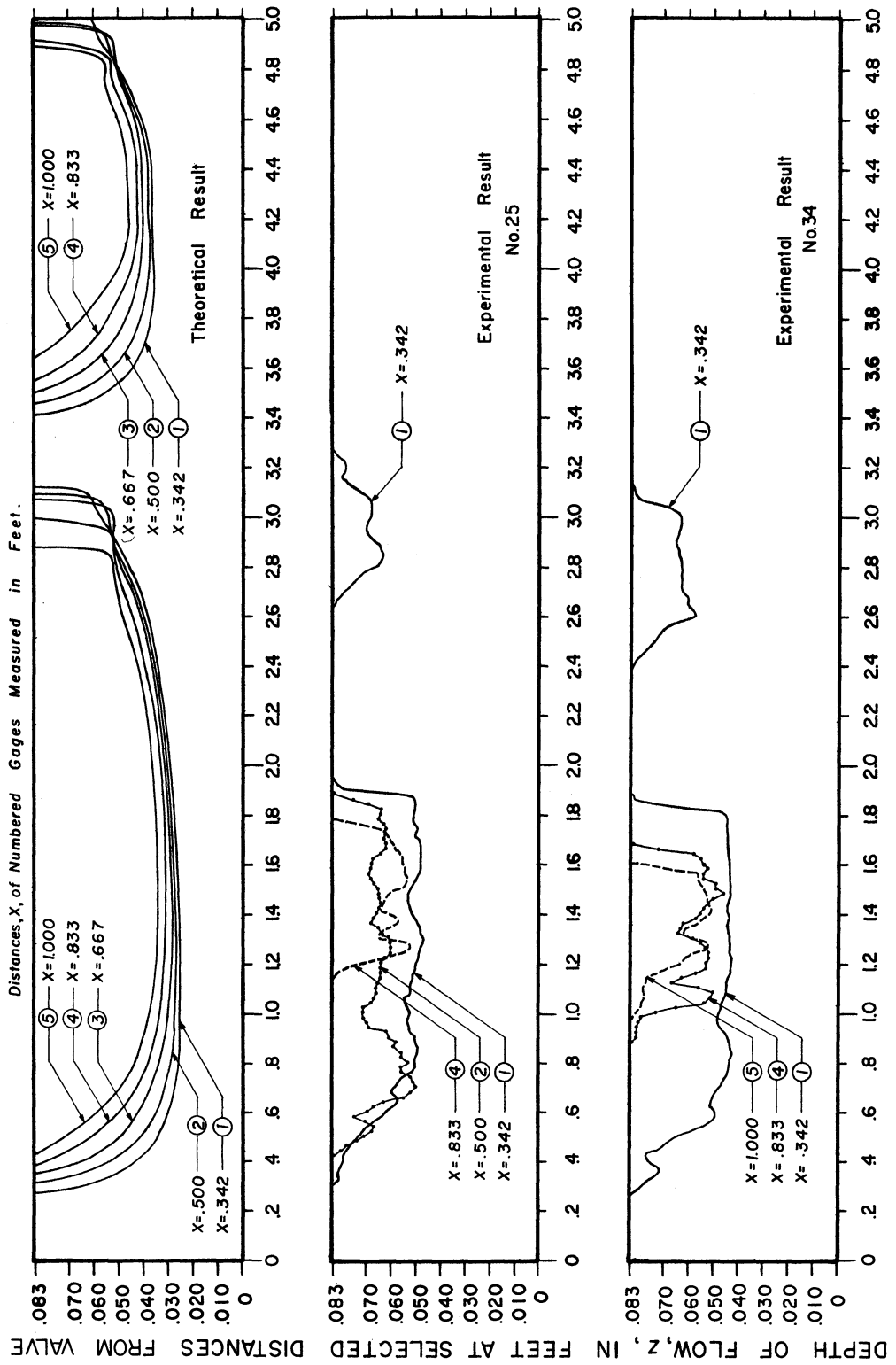

Figure 33. Comparison of the Computer-Simulated and Experimentally-Determined, Time-Dependent, Free-Surface Profiles at Selected Gages During Periods of Column Separation in the Pipe.

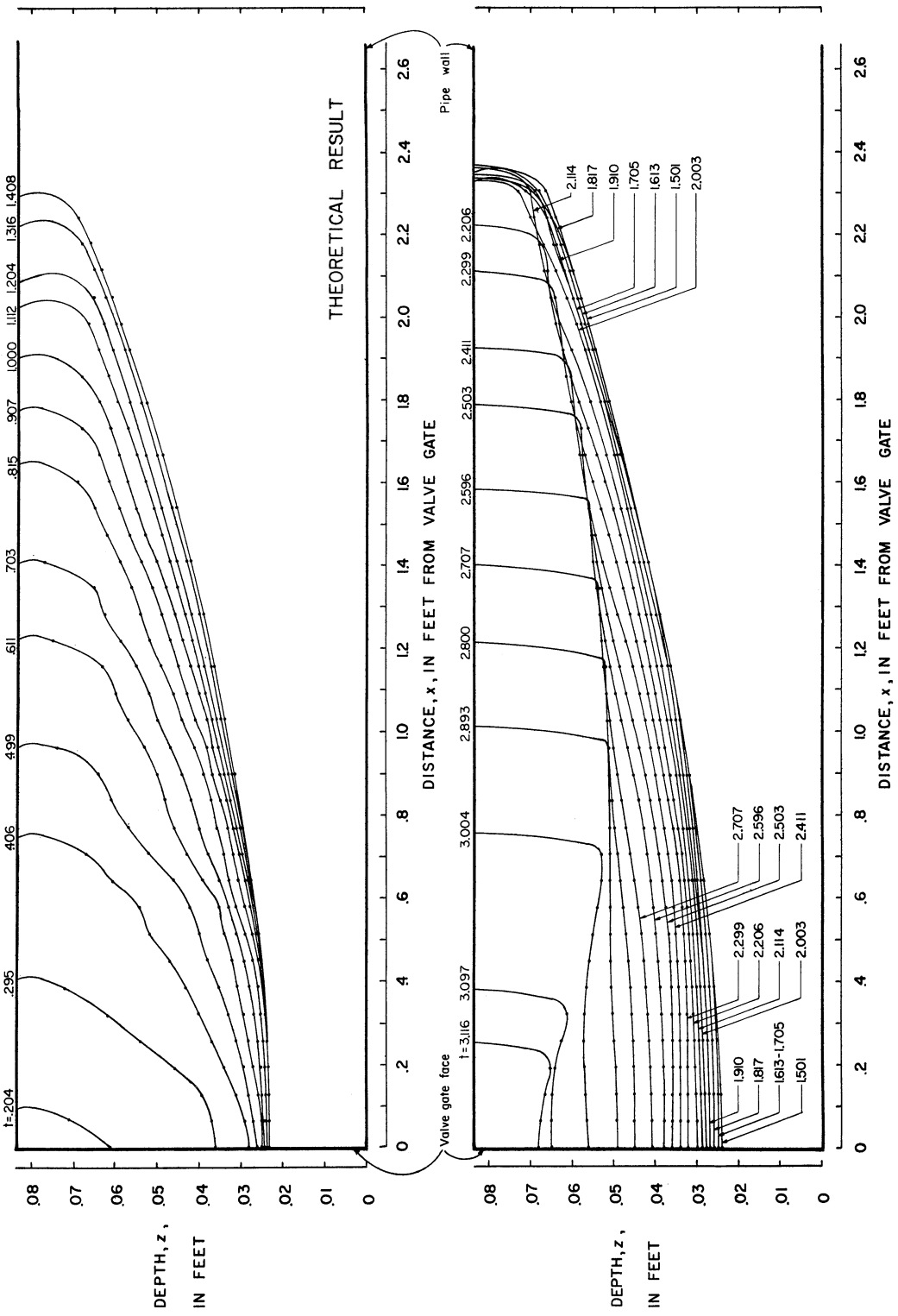

Figure 34. Computer-Simulated Sequence of Water-Surface Profiles for the Initial Period of Column Separation in the Pipe. Individual Profiles are Identified According to the Time of Their Occurrence, t , in Seconds After Closure of the Gate Valve.

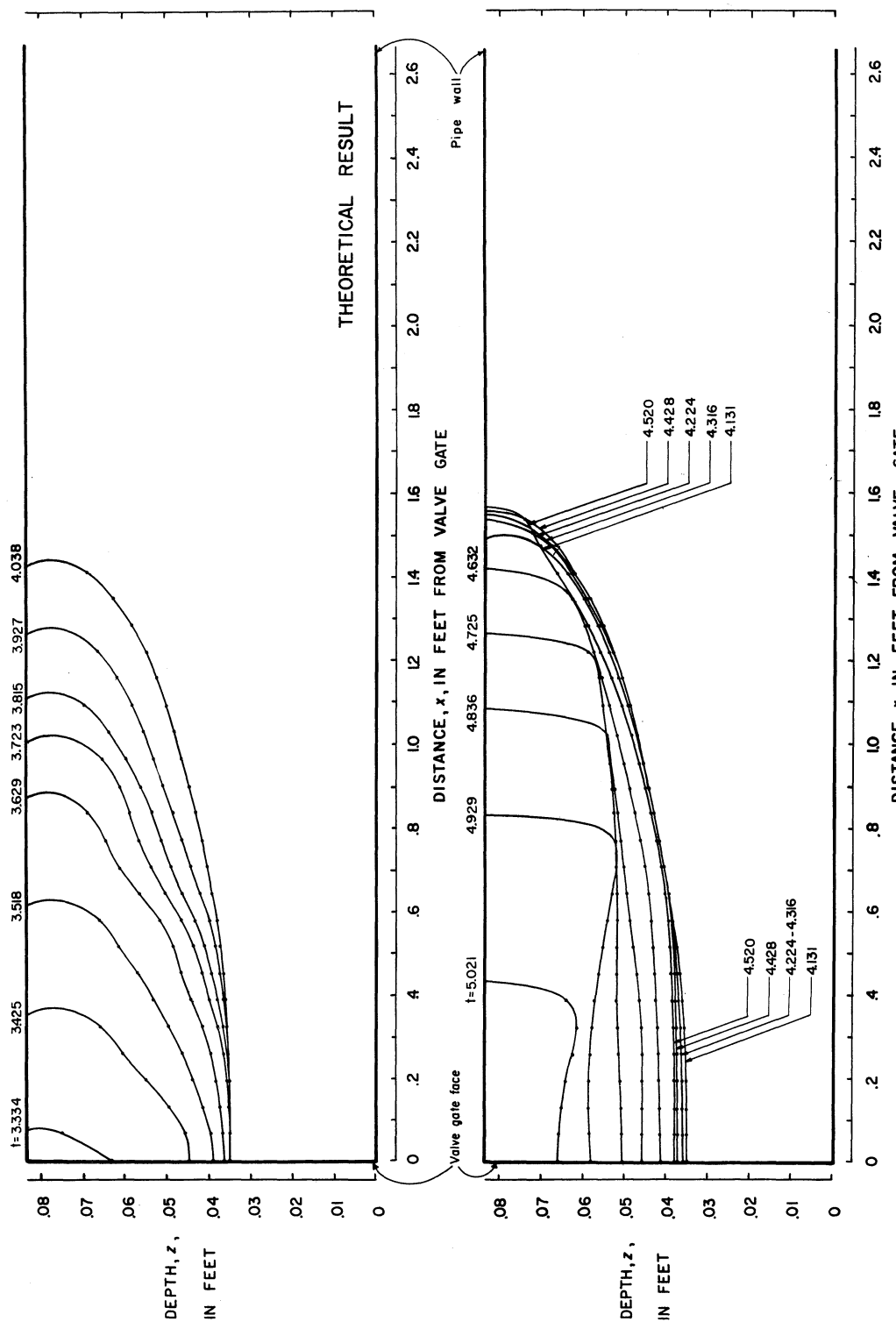

Figure 35. Computer-Simulated Sequence of Water-Surface Profiles for the Second Period of Column Separation in the Pipe. Individual Profiles are Identified According to the Time of Their Occurrence, t , in Seconds After Closure of the Gate Valve.

families of profiles derived from the mathematical model by computer simulation. Figure 34 presents the time-sequence of the water-surface profiles for the initial period of column separation; Figure 35, the water-surface profiles for the second period of column separation. Note that in both figures dissimilar horizontal and vertical scales were used. In each figure the growth sequence of the theoretical void is depicted in the top diagram while its collapse sequence is traced in the bottom diagram. Unfortunately, there were insufficient experimental data with which to plot the companion experimental curves. However, Figures 36, 37, and 38, as well as Figure 1, are typical photographs of the column-separation voids observed in the laboratory. Each of the partial profiles shown in these figures may be thought of as one profile out of a family of profiles similar to the theoretically-determined profiles of Figure 34. Because the photographs shown in Figures 36, 37, and 38 were taken at close range using a camera with a very shallow depth of field and because the inverted tape measure was positioned behind the plexiglas pipe, the apparent distances of points in the void from the gate valve are somewhat distorted and have only approximate significance.

Most of the data used in Figures 30-35 are tabulated in Appendixes III and IV.

The principal factors noted from comparing the theoretically-derived and experimentally-determined column-separation voids are cited below:

(a) The similarities which exist between the corresponding computer-simulated and experimentally-determined void profiles shown in Figures 30-34 are limited largely to similarities in the gross sense of the term. The shapes of the initial

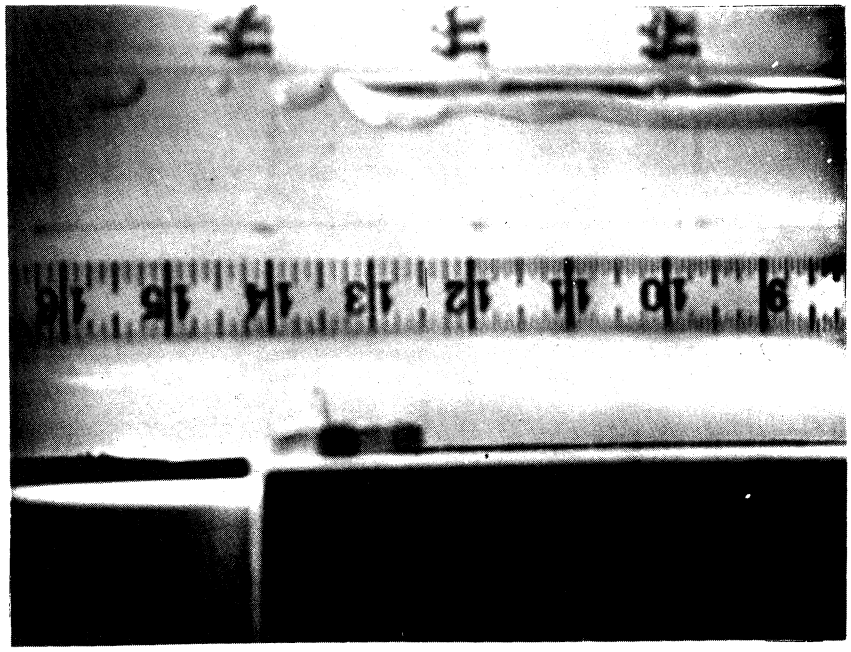

Figure 36. Advancing Column-Separation Void Photographed During Run Number 19. Inverted Scale Gives the Approximate Distance to the Inner Face of the Gate Valve in Inches.

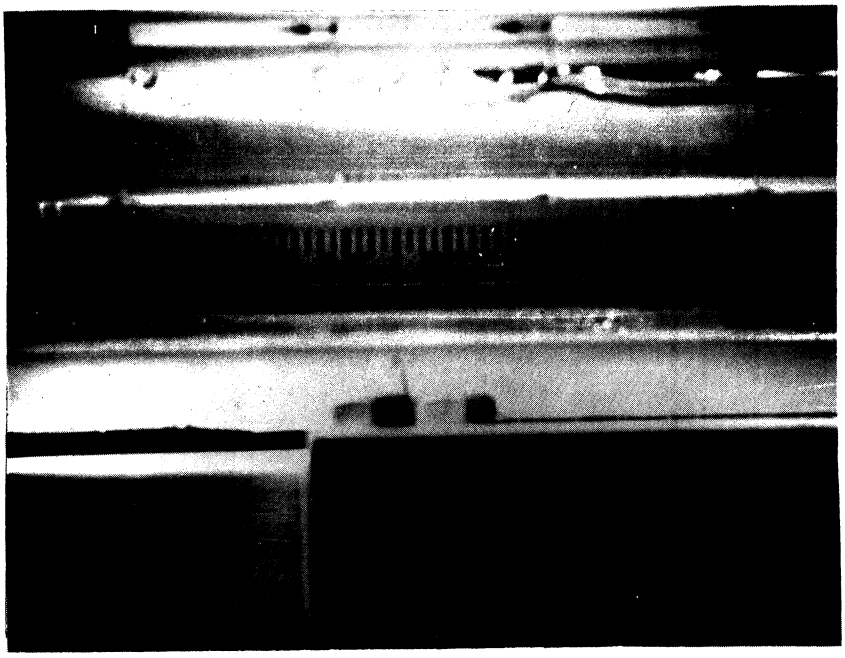

Figure 37. Advancing Column-Separation Void. Notice the Cavitation Bubbles Ahead of the Void and the Ripple Behind the Void.

Figure 38. Column-Separation Void in a State of Suspended Motion Just Prior to Retreat and Collapse Against Valve.

experimentally-determined void profiles, especially the profiles recorded at wave gage Number 1, have an identifiable resemblance to the corresponding profiles determined from theory despite topical differences and differences in duration.

(b) The shortened duration of the experimentally-determined voids is coincident with the reduced experimental recurrence interval noted in the previous section. As anticipated the extent of travel of the experimental column-separation void is much reduced -- approximately 50 percent reduced during the initial column-separation cycle -- from that which is predicted by the mathematical model. The experimental maximum extent of travel for each of the initial column-separation voids comprising Group II data is given in Table III.

(c) The depth of free-surface flow observed in all laboratory runs, but specifically as shown for runs Numbers 25 and 34, is much greater than that derived from theory. This factor, together with the reduced extent of travel, dictates that the transient volumes of the experimentally-determined voids are very much smaller than the predicted volumes.

(d) The differences between the experimental void profiles recorded at the various wave gages during laboratory runs are even more pronounced than the differences noted for the comparisons of the experimental pressure-rise data.

For example, the two experimental z - t profiles recorded at gage Number 1 have a fair resemblance to each other. Both voids form and collapse at approximately the same times respectively. Yet the associated profiles at gage Number 4 are certainly less comparable.

(e) The leading front of the experimentally-determined void is less bulbous than the front computed for the simulated void. Moreover, the front of the laboratory-produced void is usually followed by one or more surface ripples not predicted by the mathematical model (see Figures 1, 36-38).

(f) Small ripples appear on the free-surface of the experimental flow throughout the void. These ripples are not manifest on the theoretically-determined free surface profile.

(g) On the basis of comparisons with the theoretical conditions, the second experimental column-separation void has, proportionally speaking, an even smaller extent of travel than does the first experimental void.

The single most significant finding evident from the list of factors above is that the experimental void is of less physical magnitude and of less duration than is predicted by the simulation model. The shorter extent-of-travel, the greater depth of free-surface flow which conversely results in a void of shallower depth, the shorter recurrence interval, as well as the proportionally diminished extent-of-travel during the second void cycle, all lend additional support to the belief that during column separation, the rate of energy dissipation occurring in the flow ahead of the void is much higher than anticipated.

The small differences in the appearance of the leading edge of the theoretically and experimentally-determined void profiles are not unexpected. The boundary condition used with the simulation model to represent separation of flow from the pipe wall at the leading edge of the void is premised on a one-dimensional concept of the flow process. Moreover, the effects of surface tension are not considered. Thus, differences -- even greater differences than those observed -- were anticipated. Moreover, as the separation front of an advancing void moved in the pipe, a thin film of water was observed to flow around and laterally down the inner surface of the pipe and rejoin the free-surface just in back of the void front. This flow, entering the free-surface at either side of the pipe, is believed to be the cause of the rather pronounced ripple trailing the separation front of an advancing column-separation void (see Figures 36 and 37).

The factor(s) causing the other small ripples appearing on the experimental void profiles is unknown. One can speculate, however, that these ripples may have been produced by some slight pressure fluctuations occurring ahead of the separation front or by some slight anomaly in the pipe system.

Comparisons of the simulated results and the experimental results were not carried out in as great detail for the laboratory conditions of Groups II and III. However, the same general results were observed. The experimental results obtained in the laboratory had three common characteristics:

(a) Although the first pressure rise compared favorably in magnitude, form, and duration with the simulated pressure rise, the second pressure rise was of lesser magnitude than its simulated counterpart.

(b) The duration of the first experimental void was considerably shorter than the duration determined from the mathematical model.

(c) The extent-of-travel of the first experimental void was considerably shorter than predicted by simulation.

Significance of Findings

The significance of the theoretical and experimental findings cannot be interpreted properly without considering the apparent effects that cavitation and the resulting bubble flow have upon the column separation phenomena. Thus, it is of value at this point to describe in some detail the flow conditions observed in the laboratory during separation and to briefly review the role of gas nuclei and gaseous diffusion in incipient cavitation.

The formation of bubble cavities ahead of the main void was observed regularly during periods of column separation for all of the laboratory conditions investigated. The bubble cavities were observed to develop generally near the pipe wall in the topmost quadrant of the plexiglas pipe and in the portion of the flow-wake immediately behind the individual wires of the wave gages. Bubble cavities were never observed to form in the flow in the lower half of the pipe. Formation occurred very rapidly; so rapidly, in fact, that it was difficult to perceive that it occurred progressively along the pipe with time. The

ultimate size of these bubble cavities varied from nearly spherical bubbles having an approximate diameter of less than .01 foot to larger, elongated bubbles exceeding 0.3 foot in length (see Figures 1, 36, 37, 38). No variation in bubble distribution throughout the length of the plexiglas pipe could be visually detected during any given occurrence. However, the number and ultimate size of the bubble cavities did vary appreciably from one experimental run to another, even under ostensibly unchanged flow conditions. Sometimes many larger bubbles developed; at other times the bubble cavities would be predominantly smaller and more numerous.

It is noteworthy that the smaller bubble cavities appeared to move more or less with the flow whereas the larger ones moved rather sluggishly and tended to "roll" along if they moved at all. Yet, with collapse of the first column-separation void the bubble cavities collapsed and disappeared or at least diminished to a subvisual level. The bubble cavities reappeared during the second and subsequent column separation voids. However, after the collapse of the third or fourth column separation void, the largest bubble cavities did not always disappear completely. Occasionally, a few very small bubbles could be observed remaining in the flow.

It has been fairly well established that under ordinary engineering conditions the inception of cavitation in water results from the growth of submacroscopic nuclei containing liquid vapor and undissolved (free) air.[13,16,38,44] These nuclei may be present in the water, or they may be attached to the boundary surfaces or to particulate matter

in water. For a small spherical bubble in static equilibrium in water, one may write the equation

$$p_g + p_v - p_a = 2\frac{\sigma}{r} \qquad (169)$$

where p_a is the local ambient pressure, p_v is the liquid vapor pressure, p_g is the gas partial pressure, σ is the surface tension, and r is the bubble radius. The pressure, p_g, of a known weight of a perfect gas at constant temperature is

$$p_g = \frac{wRT}{V}$$

where w is the weight of the gas, T is its absolute temperature, V is its volume, and R is the gas constant (53.35 ft. lb./lb./Deg.Rankin). Thus, this expression can be written

$$p_g = \frac{3wRT}{4\pi r^3} = \frac{J}{r^3}$$

where $J = 3wRT/4\pi$ is a parameter indicative of the weight of the gas in a bubble at a particular temperature. Equation (169) becomes

$$p_a - p_v = \frac{J}{r^3} - \frac{2\sigma}{r} . \qquad (170)$$

The minimum pressure at which this equilibrium relationship is valid is found by differentiating with respect to r :

$$\frac{d(p_a - p_v)}{dr} = \frac{-3J}{r^2} + 2\sigma = 0 .$$

Therefore, the critical pressure, r* , is

$$r^* = \left(\frac{3J}{2\sigma}\right)^{1/2} .$$

Consequently, the minimum pressure, $(p_a - p_v)_{min} = p^*$, is

$$p^* = (p_a - p_v)_{min} = \frac{J}{(3J/2\sigma)^{3/2}} - \frac{2\sigma}{(3J/2\sigma)^{1/2}}$$

or simply

$$p^* = (p_a - p_v)_{min} = \frac{-4\sigma}{3r^*} \qquad (171)$$

for which the critical pressure is below the vapor pressure. If the ambient pressure is decreased even slightly, the bubble (water-vapor-air nucleus) becomes unstable and grows without bound. At greater than critical pressures the bubble is stable and assumes an equilibrium radius according to Equation (170). Figure 39 shows the static relationship between the pressure head and the bubble radius for various masses of gas as given by the parameter J. From this figure it is clear that in order for small diameter bubble nuclei to expand, the pressure must be less than the vapor pressure. Moreover, Strasberg[51] shows that bubbles having a diameter of less than 20 microns (6.6×10^{-5} foot) require negative absolute pressure for cavitation inception.

These simple bubble-nuclei equilibrium arguments are only generally relevant to the observed cavitation phenomenon, since the dynamic effects of an expanding, moving bubble are ignored. Moreover, the arguments assume constant temperature and constant air mass. Nevertheless, these arguments do provide a basis from which to appraise the laboratory findings.

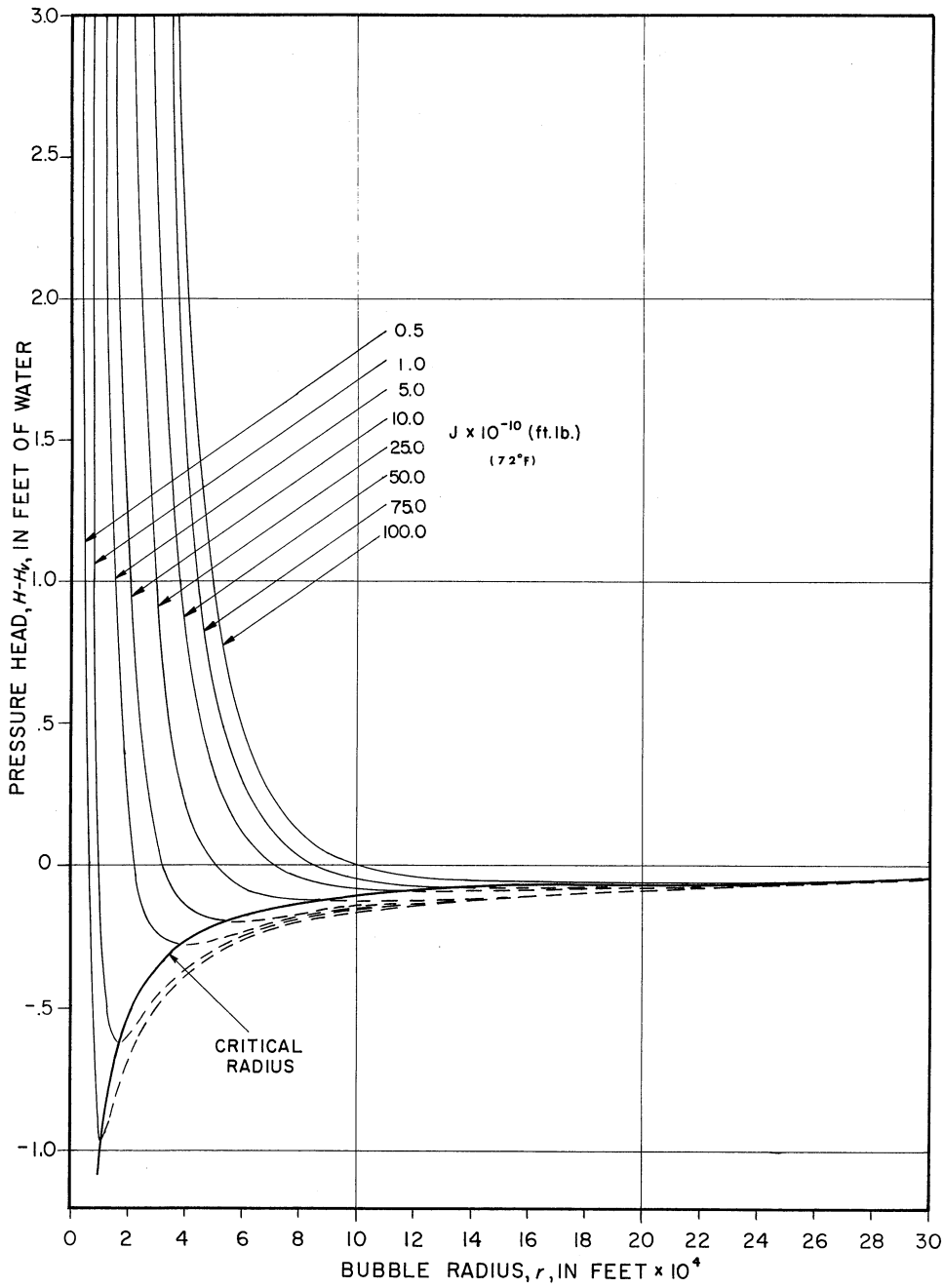

Figure 39. Diagram Relating Static Pressure to Bubble Size.

The water used in the experimental phase of the study was obtained from the main recirculated supply available in the laboratory. It was found to be nearly saturated with air under atmospheric conditions. The fact that the water must have been in a supersaturated state at the point in the laboratory flow system at which column separation occurred might lead one to presume that the cavitation may have been gaseous cavitation. However, Parkin and Kermeen[38] determined that even with convective diffusion aiding gaseous cavity growth, the time required for such growth is measured in hundreds of milliseconds, whereas, the time required for true vaporous cavitation is of the order of a few microseconds. Moreover, as noted by Strasberg[51] true vaporous cavitation is virtually independent of the dissolved air content of the water, except insofar as the dissolved air may influence the size and growth of subcritical nuclei. Vaporous cavitation with its explosive bubble growth requires the pressure to fall below the liquid vapor pressure, if only for an instant. Gaseous cavitation, on the other hand, can occur at a pressure above the vapor pressure provided this pressure is maintained long enough to sustain the comparatively slow diffusion process. Thus, three factors indicate that the main column separation void, as well as the cavitation occurring ahead of it are, in fact, of vaporous origin: (a) the almost instantaneous explosive character of bubble-cavity formation, (b) the insufficient time for gaseous cavitation, and (c) the complete (or nearly complete) disappearance of both the separation-void and bubble cavities with the sudden reoccurrence of high pressures.

Recent studies by Ripken and Killen[44] offer a possible explanation for the appearance of the vaporous bubble cavities near the top, inner surface of the pipe and in the wakes behind the wires of the

wave gages. Their research revealed that vorticity and boundary-layer turbulence promote the diffusive growth of the entrained air-water-vapor nuclei, thereby promoting vaporous cavitation in these regions at the onset of subcritical pressures.

From the laboratory observations and information pertaining to cavitation phenomena presented above, it appears that the mechanism of column separation and the accompanying bubble cavitation occurring ahead of the separation void may be described as follows: The initial high pressures in the pipe are relieved by flow of water toward the reservoir. When the motion of flow extends to the interface between the water column and the closed gate valve, tensile stresses tend to form in the water adjacent to the gate and the local pressure abruptly decreases below ambient pipe pressure. Minute quantities of dissolved air leave solution in free, molecular form and coalesce with the already present submacroscopic air-water-vapor nuclei. Pressures at the gate valve continue to decrease and to propagate from the valve toward the reservoir as a low-pressure wave. The rate of propagation is of the order of 2.5 to 4.5 x 10^3 feet per second. Concurrently, a submacroscopic nucleus in the vicinity of the topmost region of the water-column, gate-valve interface is subjected to less than the critical equilibrium condition and expands explosively. The result is formation of a column-separation void. The void continues to expand and propagate from the gate valve toward the reservoir, but with a celerity of only a few feet per second. Other nuclei situated between the propagating, low-pressure, wave and the much more slowly advancing separation void encounter less than critical conditions and expand explosively, also. These, then, are the bubble cavities observed to occur ahead of the void.

Contrary to the assumption of Chapter II that flow ahead of the separation void would be full-pipe flow, the bubble cavities produce a highly transient, metastable, two-phase flow characterized by intricate flow geometry and by ever-changing boundary conditions. The outlook for a rational interpretation of the energy dissipation rate under such conditions is dismal at best. However, the rate of energy dissipation that occurs under somewhat similar flow conditions is known to be greater than for comparable single-phase, steady-state, full-pipe flow.[57] This is so, first of all, because of the complex character of the two-phase flow pattern and, second, because of the energy losses associated with cavitation itself.[33] Nevertheless, the treatment of energy dissipation in two-phase flow, either by rational or empirical means, is beyond the scope of this study.

In order to test the notion that a higher rate of energy dissipation would shorten the duration of the theoretically-determined column separation intervals and would thereby bring the computer-simulated results into closer agreement with the experimental findings, the friction-loss coefficient in the simulation model was arbitrarily adjusted. The computer program was temporarily modified so that whenever the absolute pressure head at any point in the pipe fell below 12 feet of water during periods of column separation, the friction coefficient at that point was increased by a factor of 3. The simulated results obtained with this arbitrary modification did indeed verify the notion; the duration of the first column separation interval was decreased, the distance of travel of the separation void was reduced, and the magnitude of the second pressure rise was brought more nearly into agreement with the laboratory finding. The simulation was not carried beyond the second pressure rise.

From a qualitative point of view, the better agreement between the theoretical and experimental results tends to support the arguments for increased energy dissipation. Quantitatively speaking, however, the arbitrary increase in the friction coefficient is of no significance because the column separation phenomenon is dependent upon the following related factors:

(a) The nucleation characteristics of the water -- specifically the size spectrum and quantity of submacroscopic nuclei.

(b) The vorticity and turbulence-generating characteristics of the particular pipe.

(c) The diameter of the pipe and the velocity of the flow in the pipe.

(d) The magnitude and occurrence characteristics of the negative pressure initiating column separation.

Although iteration methods could be used to determine the friction coefficients which would bring the theoretical findings into very close agreement with each of the experimental results, such coefficients would be highly empirical and would have very little transfer value to other flow conditions. Thus, the significance of this discussion may be summarized as follows: The theoretical representation of the column separation phenomena depicted by the computer model is a limiting condition. During actual column separation under typical transient flow conditions, the separation void(s) that form will be of shorter duration and lesser extent, and the pressure rises after the initial rise will be of lesser magnitude than predicted by the mathematical model. The actual column

separation phenomena will tend to approach the theoretically predicted conditions derived from the model only when a deficiency of air, water-vapor nuclei in the water inhibits the full development of two-phase flow ahead of the void.

CHAPTER VII

CONCLUSIONS

The primary objective of the study was to provide better insight into the fluid dynamics of liquid column separation. The approach used was to develop a rational, generally applicable, mathematical model with which to numerically simulate transient flow, including liquid column separation, and thereby duplicate the essence of the phenomena without actually attaining reality. The findings derived from simulation were then systematically compared with the corresponding findings obtained from concurrent experimental investigations conducted in the laboratory. The conclusions drawn from the study are:

(a) The two sets of partial differential equations, describing the transient pressure waves in a pipe flowing full on the one hand, and transient, free-surface, gravity-type waves in the partially-full pipe on the other hand, are both of the nonlinear, hyperbolic type and directly amenable to solution by the method of characteristics. The appropriate effects of fluid friction upon each type of transient flow are readily included in the solution.

(b) By means of the appropriate boundary conditions and by considering other controlling physical parameters, a sensitive, articulate, and highly sophisticated mathematical model representing the transient-flow, column-separation phenomena can be created.

(c) Experimental laboratory studies of transient flow with column separation reveal that vaporous cavitation occurs throughout much of the length of the pipe under conditions of supposedly full-pipe flow ahead of the void. As a direct result of this cavitation, flow is temporarily transformed into highly transient, metastable, two-phase flow.

(d) Comparison of computer-simulated and experimentally-determined transient flows accompanied by column separation reveals that the mathematical model does indeed reproduce the characteristics of the phenomena, e.g. the time sequence of pressure rises at the closed valve separated by column separation voids. The magnitude, duration, and form of the first simulated pressure rise compared very favorable with its experimentally-derived equivalent. However, after the first experimental pressure rise the subsequent rises are observed to diminish in magnitude more rapidly with time than their simulated counterparts. Moreover, the duration and extent-of-travel of the successive experimental voids are also considerably less than predicted from the mathematical model.

(e) An overall similarity in shape is apparent between the experimental voids and their model-derived counterparts. However, free-surface ripples and other small perturbations are evident on the free surface of the experimental voids that do not appear on the rather idealistically smooth free surface of the simulated voids.

(f) The higher rate of energy dissipation associated with the two-phase flow produced by cavitation ahead of the void is responsible for the shortened duration and extent of the experimental voids and for the diminished magnitude of the experimental pressure rises subsequent to the first rise. Whereas the model assumes viscous energy dissipation governed by the velocity of the full-pipe flow, the two-phase, cavitation-producing flow is accompanied by thermodynamic as well as more vigorous viscous energy dissipation.

(g) Computer-simulated transient flows determined from the mathematical model represent a limit or maximum condition which will be approached only when cavitation ahead of the void is nominal. Hence, the model has direct engineering application in the determination of design criteria.

Future study of transient-flow accompanied by column-separation should be directed toward incorporating the thermodynamic aspects of liquid column separation into the mathematical model. Vaporization, heat conduction, and condensation are factors of greater significance as a result of the occurrence of cavitation ahead of the separation void.

Further experimental investigation is desirable using larger diameters of pipe and higher velocities. It is recommended that for any future experimental study stroboscopic photography be used to determine the form of the separation voids rather than the wave gages used in this study. Such a procedure would remove the possible influence of the wave gages on the formation of cavitation, provide more data on the void, and eliminate troublesome instrumentation requiring repeated calibration.

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APPENDIX I

MAIN COMPUTER PROGRAM

A complete syntactical listing of the MAD language computer program for simulation of transient flow accompanied by column separation in the pipe system shown in Figure 14 is presented below. The program, which is designated MAIN, is divided into several subsections, each of which is identified and briefly described by comments regarding its primary function. These subdivisions also correspond to the subdivisions of the flow diagram of Figure 13. All internal subroutines are included in the listings. External subroutines, however, are listed syntactically in Appendix II.

```
$ COMPILE MAD,PRINT OBJECT,EXECUTE,PUNCH OBJECT,I/O DUMP          MAIN 001          070785   04/06/64      10 27 54.8 PM
$ FULL DUMP

MAD (12 MAR 1964 VERSION) PROGRAM LISTING ... ... ...


      THIS PROGRAM IS A THEORETICAL ANALYSIS OF THE PHENOMENA OF
      LIQUID COLUMN SEPARATION IN A HORIZONTAL PIPE AS ENCOUNTERED
      UNDER CONDITIONS OF TRANSIENT FLOW.   THE PROGRAM HAS BEEN
      WRITTEN IN ''MAD'', THE MICHIGAN ALGORITHM DECODER LANGUAGE
      AND EXECUTED ON THE IBM 7090 AT THE UNIVERSITY OF MICHIGAN
      COMPUTING CENTER.

              *  *  *                              *  *  *

      INTEGER I,J,K,L,M,N,MN,GAP,MAXLIM,CUTOFF,SHUTOF,PRTLIM,PRTFRQ                *001
     0 ,PRTCYC,INCVPT,MOFSEP,MOFCOL,JJ,JJQ,KK,JHK,INC,MK,FACTOR,C,                *001
     1 SPRK,IPRK,LPRK,FVA,FVB,PMK,MARK,COUNT                                      *001
      STATEMENT LABEL STATEA,STATEB,STATEC,STATED,STATEE                          *002
      FORMAT VARIABLE FVA,FVB                                                     *003
      DIMENSION V(210,ADIM),H(210,ADIM),VP(210,ADIM),HP(210,ADIM),                *004
     0 EL(210),THETA(210,ADIM),ALPHA(200),E(2),B(2),AOG(2),                       *004
     1 LL(2),MN(2),DELTT(2),DELX(2),MU(2),A(2),ZETA(2),CP(2),                     *004
     2 GOA(2),IVEL(2),HLOS(2),U(100),Z(100),UP(100),ELP(210,ADIM)                 *004
      PROGRAM COMMON R(2),XI,D(2),PAREA,NU,GAP,F(102,DIM),ZP(100),                *005
     0 SPRK,IPRK,LPRK,FVA,FVB,STATED,NYORK,PENNSY,SUZ(11)                         *005
      VECTOR VALUES DIM = 2,1,51                                                  *006
      VECTOR VALUES ADIM = 2,1,105                                                *007
UNITED  CONTINUE                                                                  *008
      READ FORMAT CARD,RHO,KA,VMAX,GAP,HBAR,NU,Q                                  *009
      READ FORMAT PLAN,HEL,MEL,LEL,WSEL,LOC1,LOC2,LOC3                            *010
      READ FORMAT PIPE1,E(1),ZETA(1),D(1),B(1),R(1),LL(1),MN(1)                   *011
      READ FORMAT PIPE2,E(2),ZETA(2),D(2),B(2),R(2),LL(2),MN(2)                   *012
      READ FORMAT CONTRL,MAXLIM,CUTOFF,INCVPT,SHUTOF,PRTLIM,PRTFRQ                *013
     0 ,PRTCYC                                                                    *013
      READ FORMAT QUANT,INC,HVAPOR,XI,FACTOR,IOTA,ZOV                             *014
      READ FORMAT FRIC1,F(1,0)...F(1,35)                                          *015
      READ FORMAT FRIC2,F(2,0)...F(2,35)                                          *016
      READ FORMAT CSURG,SUZ(0)...SUZ(10)                                          *017
      CP(1) = 1.-ZETA(1)*((B(1)-R(1))/R(1))                                       *018
      CP(2) = 1.-ZETA(2)*((B(2)-R(2))/R(2))-ZETA(2)*ZETA(2)*(B(2)/R               *019
     0 (2))                                                                       *019
      PRINT COMMENT $1                                                            *020
     0          GIVEN INFORMATION   $                                            *020
      PRINT COMMENT $-GIVEN PHYSICAL DATA AND CONSTANTS  $                        *021
      PRINT FORMAT GIVEN,RHO,KA,VMAX,HBAR,Q                                       *022
      PRINT COMMENT $0IMENSIONAL DATA DESCRIBING ANALYTIC MODEL $                 *023
      PRINT FORMAT SCHEME,HEL,MEL,LEL,WSEL,LOC1,LOC2,LOC3                         *024
      PRINT COMMENT $0PIPE CHARACERISTICS AND RELATED DATA $                      *025
      PRINT FORMAT TUBE1,E(1),ZETA(1),D(1),B(1),R(1),LL(1),MN(1)                  *026
      PRINT FORMAT TUBE2,E(2),ZETA(2),D(2),B(2),R(2),LL(2),MN(2)                  *027
      PRINT COMMENT $0PROGRAM OPERATION AND CONTROL DATA    $                     *028
      PRINT FORMAT ORDERS,MAXLIM,CUTOFF,INCVPT,SHUTOF,PRTLIM,PRTFRQ               *029
     0 ,PRTCYC                                                                    *029
      PRINT COMMENT $0FRICTION VALUES FOR CONSECUTIVE REYNOLDS NUMB               *030
     0 ERS FROM 100 TO 35100 IN INCREMENTS OF 1000.  $                            *030

              *  *  *                              *  *  *
```

```
      PART I - PART ONE OF THIS PROGRAM IS PRIMARILY CONCERNED
      WITH THE TRANSIENT CONDITIONS IN THE FLOW SYSTEM (OR PORTION
      THEREOF) WHICH IS ALWAYS FLOWING FULL.  SEVERAL STATEMENTS
      OF INTRODUCTION AND INITIALIZATION FOLLOW.

            *  *  *                              *  *  *

      WHENEVER MN(1).E.2                                                *031
        STATEA=MICHGN                                                   *032
        STATEB=MONTAN                                                   *033
      OTHERWISE                                                         *034
        STATEA=MISSIP                                                   *035
        STATEB=MAINE                                                    *036
      END OF CONDITIONAL                                                *037
      MOFSEP = MAXLIM                                                   *038
      JJ = MAXLIM                                                       *039
      MARK=0                                                            *040
      VEGE=0.                                                           *041
      THROUGH STATES,FOR N=0,1,N.G.35                                   *042
        REYNO=100.+(N*1000.)                                            *043
STATES  PRINT FORMAT RESFAC,REYNO,N,F(1,N),N,F(2,N)                     *044
      THROUGH ALASKA, FOR J = 1,1,J.G.2                                 *045
        ZW=0(J)                                                         *046
        A(J) = SQRT.(1./(RHO*((1./KA)+(D(J)*CP(J))/(E(J)*(B(J)-R(J)     *047
     0 )))))                                                            *047
        DELX(J) = LL(J)/MN(J)                                           *048
        IVEL(J) = Q/(3.14159*R(J).P.2)                                  *049
        HLOS(J) = FFC.(ZW,IVEL(J),J)*DELX(J)*                           *050
     0   IVEL(J).P.2/(D(J)*64.32)                                       *050
ALASKA  DELTT(J) = DELX(J)/(.ABS.VMAX+.ABS.A(J))                        *051
      WHENEVER DELTT(1).GE.DELTT(2)                                     *052
        DELT = DELTT(2)                                                 *053
      OTHERWISE                                                         *054
        DELT = DELTT(1)                                                 *055
      END OF CONDITIONAL                                                *056
      THROUGH ALABAM, FOR J = 1,1,J.G.2                                 *057
        AOG(J) = A(J)/32.16                                             *058
        GOA(J) = 32.16/A(J)                                             *059
ALABAM  MU(J) = DELT/DELX(J)                                            *060

            *  *  *                              *  *  *

      PART I - SEC.A.  THIS SECTION OF PROGRAM SETS UP THE
      THEORETICAL FLOW SYSTEM BEING INVESTIGATED AND DELINEATES
      THE APPROPRIATE POINT ELEVATIONS AND SLOPES AS WELL AS THE
      VELOCITIES AND HYDRAULIC-GRADIENT HEADS UNDER STEADY STATE
      CONDITIONS.

            *  *  *                              *  *  *

      PRINT COMMENT $1                                                  *061
     0            COMPUTED RESULTS   $                                *061
      PRINT COMMENT $- COMPUTED VALUES OF ABSOLUTE PRESSURE HEAD, V     *062
     0 ELOCITY, ELEVATION, AND ANGLE OF PIPE INCLINATION AT TIME T =    *062
     1  0.   $                                                         *062
      THROUGH ARIZON, FOR N = MN(1)+MN(2),-1,N.L.0                      *063
        MARS = (N-MN(1))*DELX(2)+LL(1)                                  *064
        WHENEVER MARS.GE.LOC3                                           *065
          ALPHA(N) = 0.                                                 *066
```

```
                EL(N) = LEL                                                    *067
              OR WHENEVER MARS.GE.LOC3-DELX(2).AND.MARS.L.LOC3                 *068
                ALPHA(N) = ARCSIN.((MEL-LEL)/(LOC3-LOC2))                      *069
                EL(N) = LEL+SIN.(ALPHA(N))*(LOC3-MARS)                         *070
              OR WHENEVER MARS.GE.LOC2                                         *071
                ALPHA(N) = ALPHA(N+1)                                          *072
                EL(N) = EL(N+1)+SIN.(ALPHA(N))*DELX(2)                         *073
              OR WHENEVER MARS.GE.LOC2-DELX(2).AND.MARS.L.LOC2                 *074
                ALPHA(N) = ARCSIN.((HEL-MEL)/(LOC2-LOC1))                      *075
                EL(N) = MEL+SIN.(ALPHA(N))*(LOC2-MARS)                         *076
              OR WHENEVER MARS.GE.LOC1                                         *077
                ALPHA(N) = ALPHA(N+1)                                          *078
                EL(N) = EL(N+1)+SIN.(ALPHA(N))*DELX(2)                         *079
              OTHERWISE                                                        *080
                ALPHA(N) = 0.                                                  *081
                EL(N) = HEL                                                    *082
ARIZON        END OF CONDITIONAL                                               *083
            HABS = HSEL+HBAR                                                   *084
            THROUGH CALIF, FOR I = 0,1,I.G.MN(1)                               *085
              N = I                                                            *086
              ELP(1,I)=EL(N)                                                   *087
              H(1,I)=HABS-HLOS(2)*MN(2)-HLOS(1)*(MN(1)-N)                      *088
              V(1,I) = IVEL(1)                                                 *089
              THETA(1,I) = ALPHA(N)                                            *090
CALIF         PRINT FORMAT MEMO,I,H(1,I),I,V(1,I),I,ELP(1,I),I,THETA(1,I)      *091
            THROUGH NCARO, FOR I = 0,1,I.G.MN(2)                               *092
              N = I+MN(1)                                                      *093
              ELP(2,I)=EL(N)                                                   *094
              H(2,I)=HABS-HLOS(2)*(MN(2)-I)                                    *095
              V(2,I) = IVEL(2)                                                 *096
              THETA(2,I) = ALPHA(N)                                            *097
NCARO         PRINT FORMAT RANDUM,I,H(2,I),I,V(2,I),I,ELP(2,I),I,THETA(2,      *098
     0      I)                                                                  *098
            PRINT COMMENT $1 VALUES OF KEY VARIABLES USED THROUGHOUT THE       *099
     0 COMPUTATIONS IN PART I.   $                                             *099
            PRINT RESULTS A(1),A(2),DELX(1),DELX(2),DELTT(1),DELTT(2),         *100
     0 DELT, MU(1),MU(2),CP(1),CP(2),AOG(1),AOG(2),GOA(1),GOA(2)               *100
            VP(1,0) = V(1,0)                                                   *101
            HP(2,MN(2))=H(2,MN(2))                                             *102

                  *  *  *                          *  *  *

            PART I - SEC.B.  THIS SECTION OF THE PROGRAM CONTROLS THE
            BOUNDARY CONDITIONS USED TO INITIATE TRANSIENT FLOW IN THE
            THEORETICAL SYSTEM AND TO CREATE THE VACUOUS CAVITY
            PHENOMENA.  IT IS PRIMARILY INTENDED TO CONTROL THE
            SEQUENCE OF OPERATIONS WITH RESPECT TO TIME THROUGHOUT THE
            DURATION OF THE TRANSIENT PHENOMENON.

                  *  *  *                          *  *  *

TEXAS       THROUGH ARKANS,FOR M=1+MARK,1,M.G.MAXLIM                           *103
              WHENEVER M.G.CUTOFF                                              *104
                TRANSFER TO WVIRG                                              *105
              OR WHENEVER M.E.SHUTOF                                           *106
                VP(1,0)=0.                                                     *107
                TOFOFF = M*DELT                                                *108
                PRINT FORMAT UBOE,TOFOFF,M                                     *109
                SHUTOF=0                                                       *110
              END OF CONDITIONAL                                               *111
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                    *  *  *                              *  *  *

      PART I - SEC.C.  THIS SECTION OF THE PROGRAM COMPUTES THE
      VELOCITIES AND THE HEADS THROUGHOUT THE X-T PLANE BY THE
      METHOD OF CHARACTERISTICS FOR THE SPECIAL CASE OF THE FULL
      LENGTH OF A PIPE BEING EQUIVALENT TO AN INCREMENTAL LENGTH,
      THAT IS, EITHER THE LENGTH OF INCREMENT MN(1) = LL(1) OR THE
      LENGTH OF INCREMENT MN(2) = LL(2).

                    *  *  *                              *  *  *

HAWAII          THROUGH COLORA,FOR J=1,1,J.G.2                                  *112
                   ZW=D(J)                                                      *113
                   WHENEVER MN(J).L.2                                           *114
                     VL=V(J,0)                                                  *115
                     HL=H(J,0)                                                  *116
                     VR=V(J,1)                                                  *117
                     HR=H(J,1)                                                  *118
                     VAL=VR+(VL-VR)*(VR+A(J))*MU(J)                             *119
                     HAL=HR+(HL-HR)*(VR+A(J))*MU(J)                             *120
                     VEP=VL+(VL-VR)*(VL-A(J))*MU(J)                             *121
                     HEP=HL+(HL-HR)*(VL-A(J))*MU(J)                             *122
                     WHENEVER J.L.2.AND.M.GE.MOFSEP                             *123
                        VP(J,0)=VEP+(HP(J,0)-HEP)*GOA(J)-FFC.(ZW,VL,J)*         *124
                0          ((VL*.ABS.VL)/(2.*D(J)))*DELT+VEP*SIN.(THETA         *124
                1          (J,0))*GOA(J)*DELT                                   *124
                           PSI=VAL+HAL*(GOA(J))-FFC.(ZW,VR,J)*                  *125
                0          ((VR*.ABS.VR)/(2.*D(J)))*DELT-VAL*SIN.(THETA(J,1))   *125
                1          *(GOA(J))*DELT                                       *125
                        OR WHENEVER J.L.2                                       *126
                           HP(J,0)=HEP+(VP(J,0)-VEP)*(AOG(J))+FFC.(ZW,VL,J)*    *127
                0          ((VL*.ABS.VL)/(2.*D(J)))*DELT*AOG(J)-                *127
                1          VEP*SIN.(THETA(J,0))*DELT                            *127
                           WHENEVER (HP(1,0)-ELP(1,0)).L.HVAPOR,TRANSFER TO FL  *128
                0          ORID                                                 *128
                           PSI=VAL+HAL*(GOA(J))-FFC.(ZW,VR,J)*                  *129
                0          ((VR*.ABS.VR)/(2.*D(J)))*DELT-VAL*SIN.(THETA(J,1))   *129
                1          *(GOA(J))*DELT                                       *129
                        OR WHENEVER J.G.1                                       *130
                           CHI=VEP-HEP*(GOA(J))-FFC.(ZW,VL,J)*                  *131
                0          ((VL*.ABS.VL)/(2.*D(J)))*DELT+VEP*SIN.(THETA(J,0))   *131
                1          *(GOA(J))*DELT                                       *131
                           HP(J,0)=(1./((GOA(J))*((D(J-1)/D(J)).P.2.)+GOA(J)))  *132
                0          *(PSI*((D(J-1)/D(J)).P.2.)-CHI)                      *132
                           WHENEVER HP(J,0).L.HVAPOR+ELP(J,0).AND.M.GE.MOFSEP,  *133
                0          HP(J,0)=HVAPOR+ELP(J,0)                              *133
                           VP(J,0)=CHI+HP(J,0)*(GOA(J))                         *134
                           HP(J-1,MN(J-1))=HP(J,0)                              *135
                           VP(J-1,MN(J-1))=VP(J,0)*((D(J)/D(J-1)).P.2.)         *136
                           PSI=0.                                               *137
                           CHI=0.                                               *138
                           VP(J,1)=VAL-(HP(J,1)-HAL)*(GOA(J))                   *139
                0          -FFC.(ZW,VR,J)*((VR*.ABS.VR)/                        *139
                1          (2.*D(J)))*DELT-VAL*SIN.(THETA(J,1))*DELT*GOA(J)     *139
                        END OF CONDITIONAL                                      *140
                        TRANSFER TO COLORA                                      *141
                     END OF CONDITIONAL                                         *142

                    *  *  *                              *  *  *
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PART I - SEC.D.  THIS SECTION OF THE PROGRAM COMPUTES THE
VELOCITIES AND THE HEADS THROUGHOUT THE X-T PLANE BY THE
METHOD OF CHARACTERISTICS FOR THE GENERAL CASE, THAT IS,
FOR THE LENGTH LL(1) EQUIVALENT TO AN INTEGRAL MULTIPLE,
MN(1), OF THE INCREMENTAL LENGTH DELX(1), AND THE LENGTH
LL(2) EQUIVALENT TO AN INTEGRAL MULTIPLE, MN(2), OF THE
INCREMENTAL LENGTH DELX(2).

      *  *  *                              *  *  *

     THROUGH COLORA,FOR I=0,1,I.G.MN(J)-2                                *143
       VL=V(J,I)                                                         *144
       HL=H(J,I)                                                         *145
       VM=V(J,I+1)                                                       *146
       HM=H(J,I+1)                                                       *147
       VR=V(J,I+2)                                                       *148
       HR=H(J,I+2)                                                       *149

DETERMINATION OF PRESSURE AT BOUNDARY CONDITION X = 0, OR AT
JUNCTION BETWEEN PIPES.

       WHENEVER I.L.1                                                    *150
          VEP=VL+(VL-VM)*(VL-A(J))*MU(J)                                 *151
          HEP=HL+(HL-HM)*(VL-A(J))*MU(J)                                 *152
          WHENEVER J.L.2.AND.M.GE.MOFSEP                                 *153
             VP(J,I)=VEP+(HP(J,I)-HEP)*GOA(J)-FFC.(ZW,VL,J)              *154
0            *((VL*.ABS.VL)/(2.*D(J)))*DELT+VEP*SIN.(                    *154
1            THETA(J,I))*GOA(J)*DELT                                     *154
          OR WHENEVER J.L.2                                              *155
             HP(J,I)=HEP+(VP(J,I)-VEP)*(AOG(J))                          *156
0            +FFC.(ZW,VL,J)*((VL*.ABS.VL)/                               *156
1            (2.*D(J)))*DELT*AOG(J)-VEP*SIN.(THETA(J,I))*DELT            *156
             WHENEVER (HP(1,0)-ELP(1,0)).L.HVAPOR,TRANSFER TO            *157
0            FLORID                                                      *157
          OR WHENEVER J.G.1                                              *158
             CHI=VEP-HEP*GOA(J)-FFC.(ZW,VL,J)                            *159
0            *((VL*.ABS.VL)/(2.*D(J)))*DELT+VEP*                         *159
1            SIN.(THETA(J,I))*GOA(J)*DELT                                *159
             HP(J,I)=(1./((GOA(J-1))*((D(J-1)/D(J)).P.2.)+               *160
0            GOA(J)))*(PSI*((D(J-1)/D(J)).P.2.)-CHI)                     *160
             WHENEVER HP(J,I).L.HVAPOR+ELP(J,I).AND.M.GE.MOFS            *161
0            EP,HP(J,I)=HVAPOR+ELP(J,I)                                  *161
             VP(J,I)=CHI+HP(J,I)*(GOA(J))                                *162
             HP(J-1,MN(J-1))=HP(J,I)                                     *163
             VP(J-1,MN(J-1))=VP(J,I)*((D(J)/D(J-1)).P.2.)                *164
             PSI=0.                                                      *165
             CHI=0.                                                      *166
          END OF CONDITIONAL                                             *167
       END OF CONDITIONAL                                                *168

COMPUTATION OF PRESSURES AND VELOCITIES AT INTERIOR POINTS.

       VAL=VM+(VL-VM)*(VM+A(J))*MU(J)                                    *169
       HAL=HM+(HL-HM)*(VM+A(J))*MU(J)                                    *170
       VEP=VM+(VM-VR)*(VM-A(J))*MU(J)                                    *171
       HEP=HM+(HM-HR)*(VM-A(J))*MU(J)                                    *172
       VALLY = VAL*.ABS.VAL                                              *173
       VEPPY = VEP*.ABS.VEP                                              *174
       FFCC = FFC.(ZW,VM,J)                                              *175
```

```
                VP(J,I+1)=0.5*(VAL+VEP)+0.5*(HAL-HEP)*GOA(J)                    *176
     0          -FFCC*((VALLY+VEPPY)/(4.*D(J)))*DELT-0.5*SIN.                  *176
     1          (THETA(J,I+1))*(VAL-VEP)*GOA(J)*DELT                           *176
                HP(J,I+1)=0.5*(VAL-VEP)*AOG(J)+0.5*(HAL+HEP)                    *177
     0          -FFCC*AOG(J)*((VALLY-VEPPY)/(4.*D(J)))*DELT-0.5*SIN.           *177
     1          (THETA(J,I+1))*(VAL+VEP)*DELT                                  *177
                WHENEVER HP(J,I+1).L.HVAPOR+ELP(J,I+1).AND.M.GE.MOFSLP          *178
     0          ,HP(J,I+1)=HVAPOR+ELP(J,I+1)                                   *178

        DETERMINATION OF PRESSURE AT BOUNDARY CONDITION X =
        LL(1) + LL(2), OR AT JUNCTION BETWEEN PIPES.

                WHENEVER I.GE.MN(J)-2                                           *179
                   VAL=VR+(VM-VR)*(VR+A(J))*MU(J)                               *180
                   HAL=HR+(HM-HR)*(VR+A(J))*MU(J)                               *181
                   WHENEVER J.L.2                                               *182
                      PSI=VAL+HAL*(GOA(J))-FFC.(ZW,VR,J)                        *183
     0                *((VR*.ABS.VR)/(2.*D(J)))*DELT-VAL*                       *183
     1                SIN.(THETA(J,I+2))*GOA(J)*DELT                            *183
                   OR WHENEVER J.G.1                                            *184
                      VP(J,I+2)=VAL-(HP(2,MN(J))-HAL)*GOA(J)                    *185
     0                -FFC.(ZW,VR,J)*((VR*.ABS.VR)/                             *185
     1                (2.*D(J)))*DELT-VAL*SIN.(THETA(J,I+2))*GOA(J)*            *185
     2                DELT                                                      *185
                   END OF CONDITIONAL                                           *186
                END OF CONDITIONAL                                              *187
COLORA          CONTINUE                                                        *188
                HHOLD = H(1,0)                                                  *189
                HOLDD = V(2,MN(2))                                              *190

        MOVE FORWARD DELTA T IN THE T-DIRECTION ON X-T PLANE.

                THROUGH SCARO,FOR J=1,1,J.G.2                                   *191
                THROUGH SCARO,FOR I=0,1,I.G.MN(J)                               *192
                  V(J,I)=VP(J,I)                                                *193
SCARO             H(J,I)=HP(J,I)                                                *194

                  *  *  *                          *  *  *

        PART I - SEC.E.  THIS SECTION OF THE PROGRAM GOVERNS THE
        PRINTING OF COMPUTED RESULTS AND PROVIDES CERTAIN SWITCHING
        OF OPERATIONS TO PART II.

                  *  *  *                          *  *  *

                WHENEVER V(2,MN(2))/HOLDD.L.0.,PRINT FORMAT BASSON,M            *195
     0          *DELT+DELT/2.                                                   *195
                WHENEVER M.E.MOFSEP                                             *196
                  VEEE=VEEE+V(1,0)                                              *197
                  PRINT COMMENT $0 THE VELOCITIES AND ABSOLUTE HEADS THR        *198
     0  OUGHTOUT THE REMAINDER OF THE FULL-FLOWING PIPE SYSTEM ARE AS           *198
     1    LISTED BELOW.   $                                                     *198
                  TRANSFER TO STATEB                                            *199
                OR WHENEVER M.GE.MOFSEP.AND.M.L.JJ                              *200
                  VEEE=VEEE+V(1,0)                                              *201
                  TRANSFER TO ARKANS                                            *202
                OR WHENEVER M.GE.MOFSEP.AND.M.E.JJ                              *203
                  JJ=M*FACTOR                                                   *204
                  VEEE=VEEE+V(1,0)                                              *205
                  TRANSFER TO GEORGI                                            *206
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IOWA            CONTINUE                                                        *207
                VEEE=0.                                                         *208
                WHENEVER M.L.MOFSEP+(INCVPT*FACTOR),TRANSFER TO RHODEI          *209
                WHENEVER M.NE.JJQ,TRANSFER TO ARKANS                            *210
RHODEI          T=DELT*M                                                        *211
                PRINT FORMAT CELLO,T,M                                          *212
                PRINT COMMENT $0   VAPOR CAVITY   $                             *213
                EXECUTE PRTLAW.(PMK)                                            *214
NJERSY          PRINT FORMAT HARP,(K=SPRK,IPRK,K.G.LPRK,K*DELXC),                *215
          0     (K=SPRK,IPRK,K.G.LPRK,K),(K=SPRK,IPRK,K.G.LPRK,U(K)),            *215
          1     (K=SPRK,IPRK,K.G.LPRK,Z(K))                                      *215
                TRANSFER TO STATED                                              *216
PENNSY          EXECUTE PRTROL.(PMK)                                            *217
                TRANSFER TO NJERSY                                              *218
NYORK           JJQ=M+(PRTCYC*FACTOR)                                           *219
                PRINT COMMENT $0   FULL-FLOWING PIPE SYSTEM   $                 *220
                TRANSFER TO STATEB                                              *221
MONTAN          PRINT FORMAT FLUTE,V(1,0),V(1,1),V(1,2),V(2,0),V(2,20)          *222
          0     ,V(2,40),V(2,60),V(2,80),V(2,100),(H(1,0)-ELP(1,0)),            *222
          1     (H(1,1)-ELP(1,1)),(H(1,2)-ELP(1,2)),(H(2,0)-ELP(2,0)),          *222
          2     (H(2,20)-ELP(2,20)),(H(2,40)-ELP(2,40)),(H(2,60)-ELP(2          *222
          3     ,60)),(H(2,80)-ELP(2,80)),(H(2,100)-ELP(2,100))                  *222
                WHENEVER M.E.MARK,TRANSFER TO TEXAS                             *223
                TRANSFER TO ARKANS                                              *224
MAINE           PRINT FORMAT ORGAN,V(1,0),V(1,1),V(2,0),V(2,10),                *225
          0     V(2,20),V(2,30),V(2,40),V(2,50),(H(1,0)-ELP(1,0)),              *225
          1     (H(1,1)-ELP(1,1)),(H(2,0)-ELP(2,0)),(H(2,10)-ELP(2,10)          *225
          2     ),(H(2,20)-ELP(2,20)),(H(2,30)-ELP(2,30)),(H(2,40)-ELP          *225
          3     (2,40)),(H(2,50)-ELP(2,50))                                     *225
                WHENEVER M.E.MARK,TRANSFER TO TEXAS                             *226
                TRANSFER TO ARKANS                                              *227
              END OF CONDITIONAL                                                *228
              WHENEVER (H(1,0)-ELP(1,0)).L.(HVAPOR+1.).OR.(HHOLD-H(1,0          *229
          0   )).G.10.,TRANSFER TO DELAWA                                       *229
              WHENEVER M.L.PRTLIM,TRANSFER TO DELAWA                            *230
              WHENEVER M/PRTFRQ.NE.M/(PRTFRQ*1.),TRANSFER TO ARKANS             *231
DELAWA        T=DELT*M                                                          *232
              PRINT FORMAT TUBA,  T,M                                           *233
              TRANSFER TO STATEA                                                *234
MICHGN        PRINT FORMAT FLUTE,V(1,0),V(1,1),V(1,2),V(2,0),V(2,20)            *235
          0   ,V(2,40),V(2,60),V(2,80),V(2,100),(H(1,0)-ELP(1,0)),             *235
          1   (H(1,1)-ELP(1,1)),(H(1,2)-ELP(1,2)),(H(2,0)-ELP(2,0)),           *235
          2   (H(2,20)-ELP(2,20)),(H(2,40)-ELP(2,40)),(H(2,60)-ELP(2           *235
          3   ,60)),(H(2,80)-ELP(2,80)),(H(2,100)-ELP(2,100))                   *235
              TRANSFER TO ARKANS                                                *236
MISSIP        PRINT FORMAT ORGAN,V(1,0),V(1,1),V(2,0),V(2,10),V(2,20),          *237
          0   V(2,30),V(2,40),V(2,50),(H(1,0)-ELP(1,0)),(H(1,1)-ELP            *237
          1   (1,1)),(H(2,0)-ELP(2,0)),(H(2,10)-ELP(2,10)),(H(2,20)-           *237
          2   ELP(2,20)),(H(2,30)-ELP(2,30)),(H(2,40)-ELP(2,40)),(H(2,         *237
          3   50)-ELP(2,50))                                                    *237
ARKANS        CONTINUE                                                          *238
            TRANSFER TO CONNEC                                                  *239
```

* * * * * *

PART II - PART TWO OF THIS PROGRAM IS CONCERNED WITH THE PARTIALLY FULL PIPE FLOW (OPEN-CHANNEL FLOW) ENCOUNTERED DURING THE PRESENCE OF A VACUOUS CAVITY. MORE SPECIFICALLY, IT IS CONCERNED WITH THE FORMATION AND COLLAPSE OF A VAPOR CAVITY. SEVERAL INTRODUCTORY AND DEFINITIVE STATEMENTS

```
          FOLLOW.

                *  *  *                              *  *  *

FLORID    MOFSEP=M                                                              *240
          TOFSEP=MOFSEP*DELT                                                    *241
          PRINT FORMAT DRUM,TOFSEP,MOFSEP,TOFSLP-TOFOFF                         *242
          V(1,0)=V(1,1)                                                         *243
          H(1,0)=HVAPOR+ELP(1,0)                                                *244
          HP(1,0)=HVAPOR+ELP(1,0)                                               *245
          J=1                                                                   *246
          THROUGH NDAKOT,FOR K=0,1,K.G.INC                                      *247
NDAKOT      Z(K)=D(1)                                                           *248
          U(0)=0.                                                               *249
          U(1)=V(1,0)*ZOV                                                       *250
          U(2)=V(1,0)*ZOV                                                       *251
          PAREA=3.14159*R(1).P.2.                                               *252
          UP(0)=0.                                                              *253
          MINT=.015                                                             *254
          LAMBDA=SQRT.(PAREA*32.16/MINT)                                        *255
          DELTC=FACTOR*DELT                                                     *256
          DELXC=DELTC*(.ABS.VMAX+.ABS.LAMBDA)                                   *257
          OUTFLO=DELTC*V(1,0)*ZOV*PARLA                                         *258
          STATEC=KANSAS                                                         *259
          STATEL=OKLAHO                                                         *260
          COUNT=0                                                               *261
          YY=0.                                                                 *262
          JHK=0                                                                 *263

          DEFINITIONS OF INTERNAL FUNCTIONS

          INTERNAL FUNCTION TOPWTH.(Z)=2.*SQRT.(Z*D(1)-Z.P.2.)                  *264
          INTERNAL FUNCTION SQAGOT.(Z)=SQRT.(PFPA.(Z,J)*32.16/TOPWTH.(Z         *265
        0 ))                                                                    *265
          INTERNAL FUNCTION SQAOGT.(Z)=SQRT.(PFPA.(Z,J)/(TOPWTH.(Z)*32.        *266
        0 16))                                                                  *266
          INTERNAL FUNCTION BUBVOL.(X)=PARVOL.(PARK.(X,J),J)                    *267
          INTERNAL FUNCTION BUBEQB.(X)=BUBVOL.(X)-OUTFLO                        *268
          INTERNAL FUNCTION SURGEQ.(NX)=SIMPWV.(DELXC,MK,NX,J,YY)-              *269
        0 INFLOW                                                                *269

                *  *  *                              *  *  *

          PART II - SEC.A.  THIS SECTION OF THE PROGRAM CONSIDERS THE
          FORMATION OF THE VAPOR CAVITY.  THE INITIAL GROWTH OF THE
          CAVITY IS CONSIDERED TO OCCUR AS A FRICTIONLESS, NEGATIVE
          SURGE WAVE IN A PARTIALLY FULL-FLOWING, CIRCULAR, OPEN
          CHANNEL.  SEPARATION OF THE LIQUID AT THE TOP OF THE PIPE-
          WALL IS APPROXIMATED BY A PARABOLIC SURFACE.

                *  *  *                              *  *  *

          X=BISECT.(.001*DELXC,10*DELXC,BUBEQB.,IOTA,VIRGNA)                    *270
          KK=X/DELXC                                                            *271
          WHENEVER KK.GE.9                                                      *272
            TRANSFER TO NMEXCO                                                  *273
          OR WHENEVER KK.GE.6.AND.KK.L.9                                        *274
            DELXC=3.*DELXC                                                      *275
            KK=X/DELXC                                                          *276
            PRINT COMMENT $OTHE MAGNITUDE OF DELXC IS TRIPLE THE MINIMU         *277
```

```
0 M VALUE.   $                                                          *277
  OR WHENEVER KK.GE.3.AND.KK.L.6                                        *278
    DELXC=2.*DELXC                                                      *279
    KK=X/DELXC                                                          *280
    PRINT COMMENT $0THE MAGNITUDE OF DELXC IS DOUBLE THE MINIMU         *281
0 M VALUE.   $                                                          *281
  OTHERWISE                                                             *282
    PRINT COMMENT $0 THE MAGNITUDE OF DELXC REMAINS THE MINIMUM         *283
0  VALUE.   $                                                           *283
  END OF CONDITIONAL                                                    *284
  MUCH=DELTC/DELXC                                                      *285
  PRINT COMMENT $0 GIVEN DATA AND COMPUTED VALUES PERTINENT TO          *286
0 COMPUTATION OF FLOW FOLLOWING COLUMN SEPARATION.   $                  *286
  PRINT FORMAT AMOUNT,HVAPOR,DELXC,DELTC,MARK,MUCH,FACTOR,XI,           *287
0 INC,IOTA,PAREA                                                        *287
  SPRK=0                                                                *288
  IPRK=1                                                                *289
  LPRK=KK                                                               *290
  FVA=KK                                                                *291
  FVB=KK+1                                                              *292
  SSUZZ=USURG.(D(J)-2.*XI*R(J),J)                                       *293
KENTUC  ZP(0)=PARK.(X,J)+R(1)                                           *294
  THROUGH VRMONT, FOR K=1,1,K.G.KK                                      *295
    ZP(K)=PARK.(X-(K*DELXC),J)+R(1)                                     *296
    UP(K)=V(1,0)*ZOV+USURG.(ZP(K),J)-SSUZZ                              *297
VRMONT    WHENEVER UP(K).L.0.,UP(K)=0.                                  *298
  THROUGH SDAKOT, FOR K=0,1,K.G.KK                                      *299
    U(K)=UP(K)                                                          *300
SDAKOT    Z(K)=ZP(K)                                                    *301
  TRANSFER TO STATEE                                                    *302
OKLAHO  JJ=M+(FACTOR-1)                                                 *303
  JJQ=JJ                                                                *304
  VOID=OUTFLO                                                           *305
  PRINT COMMENT $- THE INITIAL VELOCITIES AND DEPTHS IN THE VAP         *306
0 OR CAVITY ARE LISTED BELOW.   $                                       *306
  PRINT FORMAT HARP,(K=SPRK,IPRK,K.G.LPRK,K*DELXC),(K=SPRK,IPRK         *307
0 ,K.G.LPRK,K),(K=SPRK,IPRK,K.G.LPRK,U(K)),(K=SPRK,IPRK,K.G.LPR         *307
1 K,Z(K))                                                               *307
  MK=0                                                                  *308
  TRANSFER TO HAWAII                                                    *309

        *  *  *                          *  *  *

  PART II - SEC.B.  THIS SECTION OF THE PROGRAM TREATS THE
  GROWTH AND COLLAPSE OF THE VAPOR CAVITY.   AGAIN THE METHOD
  OF CHARACTERISRICS IS UTILIZED, THIS TIME AS APPLIED TO
  OPEN-CHANNEL FLOW, IN ORDER TO DETERMINE THE VELOCITIES AND
  DEPTHS WITHIN THE CAVITY.   NON-LINEAR QUANTITIES INCLUDING
  FLOW RESISTANCE DUE TO FRICTION ARE INCLUDED.

        *  *  *                          *  *  *

GEORGI  MK=MK+KK                                                        *310
  WHENEVER MK.E.0.AND.KK.E.0                                            *311
    J=1                                                                 *312
    QOUT=DELTC*(VEEE*ZOV/FACTOR)*PAREA                                  *313
    OUTFLO=VOID+QOUT                                                    *314
    X=BISECT.(.001*DELXC,3.1*DELXC,BUBEQB.,IOTA,VIRGNA)                 *315
    KK=X/DELXC                                                          *316
    VOID=OUTFLO                                                         *317
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                PMK=MK+KK                                                        *318
                COUNT=COUNT+1                                                    *319
                WHENEVER COUNT.GE.3,TRANSFER TO WASH                             *320
                STATEE=RHODEI                                                    *321
                TRANSFER TO KENTUC                                               *322
              OR WHENEVER MK.LE.0.AND.KK.L.0                                     *323
                TRANSFER TO TENNSE                                               *324
              END OF CONDITIONAL                                                 *325
              J=1                                                                *326
              U(MK+1)=U(MK)                                                      *327
              Z(MK+1)=Z(MK)                                                      *328
              THROUGH INDIAN,FOR K=0,1,K.G.MK-1                                  *329
                UL=U(K)                                                          *330
                ZL=Z(K)                                                          *331
                UM=U(K+1)                                                        *332
                ZM=Z(K+1)                                                        *333
                UR=U(K+2)                                                        *334
                ZR=Z(K+2)                                                        *335
                WHENEVER K.L.1                                                   *336
                   QZZL=SQAGOT.(ZL)                                              *337
                   UEP=UL+(UL-UM)*(UL-QZZL)*MUCH                                 *338
                   ZEP=ZL+(ZL-ZM)*(UL-QZZL)*MUCH                                 *339
                   ZP(K)=ZEP+(UP(K)-UEP)*SQAOGT.(ZL)+FFC.(ZL,UL,J)               *340
0                  *UEP*.ABS.UEP*SQAOGT.(ZL)*DELTC                               *340
                   TRANSFER TO NHAMP                                             *341
                OTHERWISE                                                        *342
NHAMP              QZZM=SQAGOT.(ZM)                                              *343
                   UAL=UM+(UL-UM)*(UM+QZZM)*MUCH                                 *344
                   ZAL=ZM+(ZL-ZM)*(UM+QZZM)*MUCH                                 *345
                   UEP=UM+(UM-UR)*(UM-QZZM)*MUCH                                 *346
                   ZEP=ZM+(ZM-ZR)*(UM-QZZM)*MUCH                                 *347
                   UALLY=UAL*.ABS.UAL                                            *348
                   UEPPY=UEP*.ABS.UEP                                            *349
                   CFFQ=FFC.(ZM,UM,J)                                            *350
                   VZZM=SQAOGT.(ZM)                                              *351
                   UP(K+1)=0.5*(UAL+UEP)+0.5*(ZAL-ZEP)/VZZM-0.5*CFFQ*(UALLY      *352
0                  +UEPPY)*DELTC                                                 *352
                   ZP(K+1)=0.5*(ZAL+ZEP)+0.5*(UAL-UEP)*VZZM-0.5*CFFQ*VZZM*       *353
0                  (UALLY-UEPPY)*DELTC                                           *353
INDIAN          END OF CONDITIONAL                                               *354
              THROUGH IDAHO,FOR K=0,1,K.G.MK                                     *355
                U(K)=UP(K)                                                       *356
IDAHO           Z(K)=ZP(K)                                                       *357
              QOUT=DELTC*(VEEE*ZOV/FACTOR)*PAREA                                 *358
              VOID=VOID+QOUT                                                     *359
              WHENEVER QOUT.L.0.,TRANSFER TO STATEC                              *360
              WHENEVER YY.G.0.,TRANSFER TO OREGON                                *361
KANSAS        OUTFLO=VOID-SIMPQ.(J,DELXC,MK)                                     *362
              TRANSFER TO OHIO                                                   *363
OREGON        OUTFLO=VOID-(SIMPQ.(J,DELXC,MK-1))                                 *364
              MK=MK-1                                                            *365

              VAPOR CAVITY GROWTH IS DETERMINED BY THE FOLLOWING
              STATEMENTS.

OHIO          WHENEVER OUTFLO.L.0.,TRANSFER TO UTAH                              *366
              WHENEVER STATEC.E.NEBRSK                                           *367
                STATEC=KANSAS                                                    *368
                JHK=0                                                            *369
                YY=0.                                                            *370
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                END OF CONDITIONAL                                                  *371
                X=BISECT.(.001*DELXC,6.1*DELXC,BUBEQB.,IOTA,VIRGNA)                *372
                WHENEVER X.LE.DELXC                                                 *373
                  Z(MK)=PARK.(X,J)+R(1)                                             *374
                  KK=0                                                              *375
                  PMK=MK                                                            *376
                  TRANSFER TO IOWA                                                  *377
                END OF CONDITIONAL                                                  *378
                KK=X/DELXC                                                          *379
                THROUGH ILLNOI, FOR K=MK+1,1,K.G.MK+KK                              *380
                  Z(K)=PARK.(X-(DELXC*(K-MK)),J)+R(1)                               *381
                  WHENEVER Z(K).L.Z(K-1).AND.K.NE.(MK+KK),Z(K)=Z(K-1)               *382
                  U(K)=V(1,0)*ZOV+USURG.(Z(K),J)-SSUZZ                              *383
ILLNOI            WHENEVER U(K).L.0.,U(K)=0.                                        *384
                PMK=MK+KK                                                           *385
                TRANSFER TO IOWA                                                    *386

                VAPOR CAVITY SHRINKAGE IS DETERMINED BY THE SUBSEQUENT
                STATEMENTS.

NEBRSK          WHENEVER VOID.L.0,TRANSFER TO TENNSE                                *387
                OUTFLO=VOID-(SIMPQ.(J,DELXC,MK)-SIMPWV.(DELXC,MK,YY,J,0.))          *388
UTAH            INFLOW=-OUTFLO                                                      *389
                STATEC=NEBRSK                                                       *390
                WHENEVER MK.L.(1+JHK),TRANSFER TO IOWA                              *391
                NX=BISECT.(0.,5.1*DELXC,SURGEQ.,IOTA,WISCON)                        *392
                JHK=(NX+YY)/DELXC                                                   *393
                YY=(NX+YY)-(JHK*DELXC)                                              *394
                KK=-JHK                                                             *395
                PMK=MK+KK                                                           *396
                TRANSFER TO IOWA                                                    *397

                      *  *  *                          *  *  *

                PART II - SEC.C.  THIS SECTION OF THE PROGRAM RECORDS THE
                COLLAPSE OF THE VAPOR CAVITY AND CARRIES OUT THE
                REINITIALIZATION AND SWITCHING NECESSARY FOR CONTINUED
                COMPUTATION OF THE FULL-FLOWING, TRANSIENT PRESSURES AND
                VELOCITIES THROUGHOUT THE ENTIRE SYSTEM.

                      *  *  *                          *  *  *

TENNSE          CONTINUE                                                            *398
                MOFCOL=M                                                            *399
                TOFCOL=DELT*MOFCOL                                                  *400
                PRINT FORMAT PICCLO,TOFCOL,MOFCOL,TOFCOL-TOFSEP,TOFCOL-TOFOFF       *401
                MOFSEP=MAXLIM+2                                                     *402
                JJ=MAXLIM+2                                                         *403
                VP(1,0)=0.                                                          *404
                VOID=0.                                                             *405
                VEEE=0.                                                             *406
                MARK=M                                                              *407
                TRANSFER TO STATEB                                                  *408
WVIRG           PRINT COMMENT $OCOMPUTATION HAS BEEN HALTED BY CUTOFF.  $           *409
                TRANSFER TO WYOMNG                                                  *410
VIRGNA          PRINT COMMENT $O SUBROUTINE 'BISECT' IS UNABLE TO FIND ROOT.$       *411
                TRANSFER TO WYOMNG                                                  *412
WISCON          PRINT COMMENT $O SUBROUTINE 'BISECT' COULD NOT FIND ROOT NX.$       *413
                TRANSFER TO WYOMNG                                                  *414
CONNEC          PRINT COMMENT $OCOMPUTATION HAS BEEN HALTED BY EXCEEDING MAXL       *415
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     0 IM.   $                                                          *415
       TRANSFER TO WYOMNG                                               *416
NMEXCO   PRINT COMMENT $OTHE MAGNITUDE OF KK EXCEEDS NINE TIMES DELXC   *417
     0 WHICH IS CONSIDERED TO BE EXCESSIVE.   COMPUTATION IS BEING H    *417
     1 ALTED FOR THIS REASON.   $                                       *417
       TRANSFER TO WYOMNG                                               *418
WASH   PRINT COMMENT $OTHE VAPOR CAVITY IS OF INSUFFICIENT MAGNITUDE    *419
     0  TO WARRENT FURTHER INVESTIGATION.   COMPUTATION IS BEING HAL     *419
     1 TED FOR THIS REASON.   $                                         *419
WYOMNG   CONTINUE                                                       *420
       VECTOR VALUES CARD =$F4.2,S5,E10.4,S5,F4.2,S6,I5,S6,F6.3,        *421
     0 S6,F8.7,S1,F6.4    *$                                           *421
       VECTOR VALUES PLAN =$F7.3,S2,6(F7.3,S3)    *$                    *422
       VECTOR VALUES PIPE1 =$E10.4,S4,F4.3,S1,3(F6.5,S4),F7.3,S3,I3     *423
     0 *$                                                               *423
       VECTOR VALUES PIPE2 =$E10.4,S4,F4.3,S1,3(F6.5,S4),F7.3,S3,I3     *424
     0 *$                                                               *424
       VECTOR VALUES QUANT = $I3,S7,F6.3,S4,F4.3,S4,I2,S4,F6.5,S4,F4    *425
     0 .2   *$                                                          *425
       VECTOR VALUES CONTRL = $2(I4,S6),(I1,S9),(I2,S8),2(I4,S6),       *426
     0 (I1,S9)   *$                                                     *426
       VECTOR VALUES GIVEN =$1H ,S2,6HRHO = F5.3,S7,5HKA = E10.4,S6,    *427
     0 7HVMAX = F4.2,S6,7HHBAR = F6.3,S8,4HQ = F6.4   *$                *427
       VECTOR VALUES SCHEME =$1H ,S2,6HHEL = F7.3,S5,6HMEL = F7.3,      *428
     0 S8,6HLEL = F7.3,S4,7HWSEL = F7.3,S4,7HLOC1 = F7.3,S4,7HLOC2 =    *428
     1  F7.3,S5,7HLOC3 = F7.3 *$                                        *428
       VECTOR VALUES TUBE1 =$1H ,S2,7HE(1) = E10.4,S4,10HZETA(1) = F    *429
     0 4.3,S4,7HD(1) = F6.5,S4,7HB(1) = F6.5,S5,7HR(1) = F6.5,S5,8HL    *429
     1 L(1) = F7.3,S4,8HMN(1) = I3 *$                                   *429
       VECTOR VALUES TUBE2 =$1H ,S2,7HE(2) = E10.4,S4,10HZETA(2) = F    *430
     0 4.3,S4,7HD(2) = F6.5,S4,7HB(2) = F6.5,S5,7HR(2) = F6.5,S5,8HL    *430
     1 L(2) = F7.3,S4,8HMN(2) = I3 *$                                   *430
       VECTOR VALUES FRIC1=$12(F5.4,S1)   *$                            *431
       VECTOR VALUES FRIC2=$12(F5.4,S1)   *$                            *432
       VECTOR VALUES CSURG=$F2.1,10(S1,F6.5)   *$                       *433
       VECTOR VALUES RESFAC=$1H ,S23,15HREYNOLDS NO. = F6.0,S15,4HF(    *434
     0 1,I2,4H) = F5.4,S15,4HF(2,I2,4H) = F5.4*$                        *434
       VECTOR VALUES MEMO =$ S11,4HH(1,I3,4H) = F7.3,S15,4HV(1,I3,4H    *435
     0 ) = F6.3,S15,6HELP(1,I3,4H) = F7.3,S13,8HTHETA(1,I3,4H) = F6.    *435
     1 3   *$                                                           *435
       VECTOR VALUES RANDUM =$ S11,4HH(2,I3,4H) = F7.3,S15,4HV(2,I3,    *436
     0 4H) = F6.3,S15,6HELP(2,I3,4H) = F7.3,S13,8HTHETA(2,I3,4H) = F    *436
     1 6.3   *$                                                         *436
       VECTOR VALUES TUBA = $1HO,S1,12HAT TIME T = F8.5,16H SECONDS,    *437
     0  AFTER I4,89H COMPLETE CYCLES OF OPERATION, THE VELOCITIES AN     *437
     1 D PRESSURES AT KEY POINTS THROUGHOUT THE /1H ,S1,35HFLOW SYST    *437
     2 EM ARE AS TABULATED BELOW.   *$                                  *437
       VECTOR VALUES FLUTE = $1HO,S4,4HLOC.,S7,5H(1,0),S8,5H(1,1),S8    *438
     0 ,5H(1,2),S8,5H(2,0),S8,6H(2,20),S7,6H(2,40),S7,6H(2,60),S7,6H    *438
     1 (2,80),S7,7H(2,100)  /1H ,S5,1HV,S6,9(S2,F8.4,S3)  /1H ,S5,1H    *438
     2 H,S6,9(S2,F8.4,S3)   *$                                          *438
       VECTOR VALUES ORGAN = $1HO,S4,4HLOC.,S6,5H(1,0),S10,5H(1,1),S    *439
     0 10,5H(2,0),S10,6H(2,10),S9,6H(2,20),S9,6H(2,30),S9,6H(2,40),S    *439
     1 9,6H(2,50) /1H ,S5,1HV,S5,7(S2,F8.4,S5),S2,F8.4,S2 /1H ,S5,1H    *439
     2 H,S5,7(S2,F8.4,S5),S2,F8.4,S3   *$                               *439
       VECTOR VALUES OBOE = $1H-,S1,83HTHE GATE VALVE AT LOCATION J     *440
     0 = 1,I = 0 HAS BEEN INSTANTANEOUSLY CLOSED AT TIME T = F8.5,      *440
     1 34H, SECONDS, OR AT OPERATION NUMBER I2,1H.   *$                 *440
       VECTOR VALUES ORDERS=$1H ,S2,31HMAXIMUM ALLOWABLE ITERATIONS     *441
     0 =  I4,S3,29HCOMPUTATION CUTOFF LIMIT   = I4,S3,26HINITIAL CAV    *441
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1 ITY PRINTOUT = I1,S3,22HVALVE SHUTOFF POINT = I2 /1H ,S2,31HI
2 NITIAL PRINTOUT LIMIT POINT = I4,S3,29HPRINTOUT FREQUENCY CON
3 TROL = I4,S3,26HCAVITY PRINTOUT CYCLE    = I1    *$
  VECTOR VALUES DRUM=$1H-,S1,61HCOLUMN SEPARATION HAS OCCURRED
0 AT THE GATE VALVE AT TIME T = F8.5,30H SECONDS (OPERATION CYC
1 LE NO. I4,13H).    THIS IS F8.5/1H ,S1,40HSECONDS AFTER CLOSUR
2 E OF THE GATE VALVE.    *$
  VECTOR VALUES AMOUNT = $1H ,S2,9HHVAPOR = F7.4,S15,8HDELXC =
0 F7.4,S15,8HDELTC = F8.5,S10,8HMARK =  I4,S12,7HMUCH = F6.4/
1 1H ,S2,10HFACTOR =    I2,S22,5HXI = F7.4,S17,6HINC = I3,S
2 15,7HIOTA = F5.4,S11,8HPAREA = F7.5    *$
  VECTOR VALUES PICCLO = $1H-,S1,54HTHE VAPOR CAVITY HAS COMPLE
0 TELY COLLAPSED AT TIME T = F8.5,30H SECONDS (OPERATION CYCLE
1 M = I4,13H).    THIS IS F8.5,9H SECONDS /1H ,S1,38HAFTER COLUM
2 N SEPARATION OCCURRED, AND F8.5,32H SECONDS AFTER VALVE WAS C
3 LOSED.    *$
  VECTOR VALUES CELLO = $1HO,S1,12HAT TIME T = F8.5,16H SECONDS
0 , AFTER I4,87H COMPLETE CYCLES OF OPERATION, THE VELOCITIES A
1 ND DEPTHS IN THE VAPOR CAVITY AS WELL AS /1H ,S1,89HVELOCITIE
2 S AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE
3 AS TABULATED BELOW.    *$
  VECTOR VALUES HARP = $1HO,S4,5HDIST.,S1,F6.4,'FVA'(S2,F6.4)/1
0 H ,S4,4HLOC.,'FVB'(S5,I2,S1)/1H ,S5,1HU,S2,'FVB'(S2,F6.3)/1H
1  ,S5,1HZ,S2,'FVB'(S3,F5.3)    *$
  VECTOR VALUES BASSON = $1H-,S1,87HTHE DIRECTION OF FLOW AT TH
0 E RESERVOIR END OF THE PIPE SYSTEM HAS REVERSED AT TIME T = F
1 8.5,9H SECONDS.    *$
  TRANSFER TO UNITED
  END OF PROGRAM
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MAC PROGRAM,TYPE 25 MAR 1964   (ALL NUMBERS ARE OCTAL)

 NO. OF LOCATIONS 17735 TRA VECTOR SIZE   00026       TRA VECTOR STARTS 00352   ENTRY PT. 05657   ERASABLE STARTS 77777

VARIABLE STORAGE (A=ARRAY,C=COMMON,E=ERASABLE,DIGIT=MODE)
     ADIM   00454 A 1        FVB    10332  C1       LL     03145 A 0        PIPE2  03451 A 1        UEPPY  04235   0
     ALABAM 00406   4        GAP    10011  C1       LOC1   03146   0        PLAN   03455 A 1        UEP    04236   0
     ALASKA 00406   4        GEORGI 00414   4       LOC2   03147   0        PMK    03456   1        UL     04237   0
     ALPHA  00765 A 0        GIVEN  02204 A 1       LOC3   03150   0        PRTCYC 03457   1        UM     04240   0
     AMOUNT 01026 A 1        GOA    02207 A 0       LPRK   10330  C1       PRTFRQ 03460   1        UNITED 00443   4
     AOG    01031 A 0        HABS   02210   0       MAINE  00421   4        PRTLIM 03461   1        UP     04405 A 0
     ARIZON 00406   4        HAL    02211   0       MARK   03151   1        PSI    03462   0        UR     04406   0
     ARKANS 00407   4        HARP   02237 A 1       MARS   03152   0        QOUT   03463   0        U      04553 A 0
     A      01034 A 0        HAWAII 00415   4       MAXLIM 03153   1        Q      03464   0        UTAH   00444   4
     BASSON 01060 A 1        HBAR   02240   0       MEL    03154   0        QUANT  03474 A 1        VALLY  04554   0
     B      01063 A 0        HEL    02241   0       MEMO   03176 A 1        QZZL   03475   0        VAL    04555   0
     CALIF  00406   4        HEP    02242   0       MICHGN 00422   4        QZZM   03476   0        VEEE   04556   0
     CARD   01075 A 1        HHOLD  02243   0       MINT   03177   0        RANDUM 03520 A 1        VEPPY  04557   0
     CELLO  01146 A 1        HLOS   02246 A 0       MISSIP 00423   4        RESFAC 03536 A 1        VEP    04560   0
     CFFQ   01147   0        HL     02247   0       MK     03200   1        REYNU  03537   0        VIRGNA 00445   4
     CHI    01150   0        HM     02250   0       MN     03203 A 1        RHODEI 00434   4        VL     04561   0
     COLORA 00410   4        HOLDD  02251   0       MOFCOL 03204   1        RHO    03540   0        VMAX   04562   0
     CONNEC 00411   4        HP     02574 A 0       MOFSEP 03205   1        R      10002 AC0        VM     04563   0
     CONTRL 01160 A 1        HR     02575   0       MONTAN 00424   4        SCARO  00406   4        VOID   04564   0
     COUNT  01161   1        H      03120 A 0       M      03206   1        SCHEME 03565 A 1        VP     05107 A 0
     CP     01164 A 0        HVAPOR 03121   0       MUCH   03207   0        SDAKOT 00406   4        VRMONT 00406   4
     CSURG  01170 A 1        IDAHO  00406   4       MU     03212 A 0        SHUTOF 03566   1        VR     05110   0
     CUTOFF 01171   1        ILLNOI 00406   4       NCARO  00406   4        SPRK   10326  C1       V      05433 A 0
     DELAWA 00412   4        INC    03122   1       NDAKOT 00406   4        SSUZZ  03567   0        VZZM   05434   0
     DELTC  01172   0        INCVPT 03123   1       NEBRSK 00425   4        STATEA 00435   4        WASH   00446   4
     DELT   01173   0        INDIAN 00406   4       NHAMP  00426   4        STATEB 00436   4        WISCON 00447   4
     DELTT  01176 A 0        INFLOW 03124   0       NJERSY 00427   4        STATEC 00437   4        WSEL   05435   0
     DELXC  01177   0        IOTA   03125   0       NMEXCO 00430   4        STATED 10333  C4       WVIRG  00450   4
     DELX   01202 A 0        IOWA   00416   4       N      03213   1        STATEE 00440   4        WYOMNG 00451   4
     DIM    01205 A 1        IPRK   10327  C1       NU     10010  C0       STATES 00406   4        XI     10003  C0
     DRUM   01245 A 1        I      03126   1       NX     03214   0        SUZ    10351 AC0        X      05436   0
     D      10006 AC0        IVEL   03131 A 0       NYORK  10334  C4       TENNSE 00441   4        YY     05437   0
     ELP    01570 A 0        JHK    03132   1       OBOE   03245 A 1        TEXAS  00442   4        ZAL    05440   0
     EL     02113 A 0        JJQ    03133   1       OHIO   00431   4        THETA  04112 A 0        ZEP    05441   0
     E      02116 A 0        JJ     03134   1       OKLAHO 00432   4        TOFCOL 04113   0        ZETA   05444 A 0
     FACTOR 02117   1        J      03135   1       ORDERS 03322 A 1        TOFOFF 04114   0        ZL     05445   0
     FFCC   02120   0        KANSAS 00417   4       OREGON 00433   4        TOFSEP 04115   0        ZM     05446   0
     FLORID 00413   4        KA     03136   0       ORGAN  03363 A 1        T      04116   0        ZOV    05447   0
     FLUTE  02157 A 1        KENTUC 00420   4       OUTFLO 03364   0        TUBA   04156 A 1        ZP     10325 AC0
     FRIC1  02162 A 1        KK     03137   1       PAREA  10007  C0       TUBE1  04204 A 1        ZR     05450   0
     FRIC2  02165 A 1        K      03140   1       PENNSY 10335  C4       TUBE2  04232 A 1        Z      05615 A 0
     F      10160 AC0        LAMBDA 03141   0       PICCLO 03433 A 1        UALLY  04233   0        ZW     05616   0
     FVA    10331  C1        LEL    03142   0       PIPE1  03442 A 1        UAL    04234   0

FUNCTION DICTIONARY
     .03310 00352   0        .01300 00353   0       .01301 00354   0        .03311 00355   0        ARCSIN 00356   0
     BISECT 00357   0        FFC    00360   0       .PCOMT 00361   0        .PRINT 00362   0        .PRSLT 00363   0
     .READ  00364   0        PARK   00365   0       PARVOL 00366   0        PFPA   00367   0        PRTLAW 00370   0
     PRTRUL 00371   0        SIMPQ  00372   0       SIMPWV 00373   0        SIN    00374   0        SQRT   00375   0
     SYSTEM 00376   0        USURG  00377   0       BUBEQB 00400   0        BUBVOL 00401   0        SQAGOT 00402   0
     SQAOGT 00403   0        SURGEQ 00404   0       TOPWTH 00405   0

ABSOLUTE CONSTANTS
05617 +203506314631     05620 +203606314631     05621 +202614631463     05622 +000000000003     05623 +202600000000
05624 +000000000006     05625 +000000000011     05626 +167406111564     05627 +172753412172     05630 +204500000000
```

APPENDIX II

SUBROUTINE PROGRAMS USED WITH MAIN COMPUTER PROGRAM

A syntactical listing for each of the 11 MAD language external subroutines used in the computer program called MAIN (See Appendix I) is presented below. The subroutines are listed according to name and function:

	Name	Function
1.	PARK	Given a distance measured from the leading edge of the separation void, the subroutine returns the depth of flow based on the parabolic free surface (See Figure 12) described in Chapter IV.
2.	PARLN	Given a depth on the free surface flow, the subroutine returns the distance to the leading edge of the separation void based on the parabolic surface (See Figure 12) described in Chapter IV.
3.	PFPA	This subroutine determines the cross-sector area of a pipe flowing partially full. The computation is based on flow depth.
4.	BISCT	This subroutine is used to determine the exact length of a separation void that extends at least n , but not (n+1) increments of length. The exact distance of the leading edge of the void from the n-th increment is computed using equilibrium between void volume and total outflow.
5.	FFC	Given the depth of flow, the velocity of flow, and the pipe segment identification, this subroutine returns the friction coefficient based upon Reynold's number. If the depth of

Name	Function
	of flow is equal to the diameter of the pipe, the coefficient is that for pipe flow; if less than the diameter of the pipe, then the coefficient is for free surface flow.
6. SIMPQ	Given the number of length increments, ΔXC , from the valve to the grid point nearest the separation void, the function returns the total volume of the void.
7. PARVOL	Given the depth of flow at a point less than an increment of length from the leading edge of the void, this subroutine returns the volume of the subincremental void determined by the parabolic surface.
8. PINTR	Given the number of increments, ΔXC , from the valve to the separation void, the subincremental distance to the leading edge of the void, and the size of the increments, the subroutine computes and returns the parabolically interpolated depth of flow from known depths.
9. SMPVL	Given the negative distance, NX , along with other controlling parameters, this function gives the incremental volume removed from the void during collapse.
10. PRINT	This function, with PRTLAW and PRTRUL providing double entry points, controls the print format to accommodate the data produced.
11. USURG	This function is used to approximate the velocity at the first grid point behind the separation void. The velocity is prorated according to depth-of-flow using the velocity ahead of the void and the free-surface propagation velocity.

MAD (12 MAR 1964 VERSION) PROGRAM LISTING ... ...

```
      EXTERNAL FUNCTION (C,L)                                                    *001
      INTEGER J,L                                                                *002
      PROGRAM COMMON R(2),XI,D(2),PAREA,NL,GAP,F(102,DIM),ZP(100),               *003
     0 SPRK,IPRK,LPRK,FVA,FVB,STATED,MYCRK,PENNSY,SUZ(11)                        *004
      VECTOR VALUES DIM = 2,1,51                                                 *005
      ENTRY TO PARK.                                                             *006
      J=L                                                                        *007
      X=C                                                                        *008
      ALPHA = (1.-2.*XI)                                                         *009
      K=ALPHA*R(J)-SQRT.(4.*XI*R(J)*X)                                           *010
      FUNCTION RETURN K                                                          *011
      END OF FUNCTION
```

```
$  COMPILE MAD,PRINT OBJECT,EXECUTE,DUMP,PUNCH OBJECT          PARLT.01          370/13   04/24/64        12 22.1 AM

MAD (12 MAR 1964 VERSION) PROGRAM LISTING ... ... ...

            EXTERNAL FUNCTION (R,L)                                                    *001
            INTEGER L,J                                                                *002
            PROGRAM COMMON R(2),XI,D(2),PAREA,NC,GAP,F(102,DIM),ZP(100),               *003
          0 SPRK,IPRK,LPRK,FVA,FVB,STATED,NYORK,PENNSY,SUZ(11)                         *004
            VECTOR VALUES DIM = 2,1,91                                                 *005
            ENTRY TO PARLEN.                                                           *006
            J=L                                                                        *007
            K=8                                                                        *008
            ALPHA = (1.-2.*XI)                                                         *009
            X=(K-ALPHA*R(J)).P.2./(4.*XI*R(J))                                         *010
            FUNCTION RETURN X                                                          *011
            END OF FUNCTION
```

```
$  COMPILE MAD,PRINT OBJECT,EXECUTE,DUMP,PUNCH OBJECT          PFPA. 01          070218   04/04/64      ; 12 26.5 AM

MAD (12 MAR 1964 VERSION) PROGRAM LISTING ... ... ...


      EXTERNAL FUNCTION (P,L)                                                    *001
      INTEGER J,L                                                                *002
      PROGRAM COMMON R(2),XI,D(2),PAREA,NL,GAP,F(102,DIM),ZP(100),               *003
     0 SPRK,IPRK,LPRK,FVA,FVB,STATED,NYORK,PENNSY,SUZ(11)                        *003
      VECTOR VALUES DIM = 2,1,51                                                 *004
      ENTRY TO PFPA.                                                             *005
      J=L                                                                        *006
      B=P                                                                        *007
        ALPHA=2.*R(J)*R(J)*ARCSIN.(SQRT.(B/(2.*R(J))))+(B-R(J))*SQR              *008
     0  T.(2.*R(J)*B-B*B)                                                       *008
      FUNCTION RETURN ALPHA                                                      *009
      END OF FUNCTION                                                            *010
```

```
$ COMPILE MAD,PRINT OBJECT, PUNCH OBJECT, EXECUTE, DUMP          BISCT.01          070218   04/04/64      9 12 31.1 AM

MAD (12 MAR 1964 VERSION) PROGRAM LISTING ... ... ...


                EXTERNAL FUNCTION (L,R,F.,LIM,K)                                  *001
                STATEMENT LABEL K                                                 *002
                ENTRY TO BISECT.                                                  *003
                XL=L                                                              *004
                XR=R                                                              *005
                IOTA = LIM                                                        *006
                FL = F.(XL)                                                       *007
                THROUGH DRUM, FOR H=XR-XL,-H/2.,H.L.(XR-XL)/32.                   *008
                THROUGH DRUM, FOR X=XL,H,(X+H).G.XR                               *009
DRUM            WHENEVER FL*F.(X+H).L.0, TRANSFER TO GONG                         *010
                TRANSFER TO K                                                     *011
GONG            THROUGH TUBA,FOR H=H/2.,-H/2.,FL*F.(X+H).G.0.                     *012
TUBA            WHENEVER H.L.IOTA, FUNCTION RETURN X                              *013
                X=X+H                                                             *014
                TRANSFER TO GONG                                                  *015
                END OF FUNCTION                                                   *016
```

MAD (12 MAR 1964 VERSION) PROGRAM LISTING ... ...

```
                EXTERNAL FUNCTION (P,V,S)                                       *001
                PROGRAM COMMON R(2),XI,D(2),PAREA,NU,GAP,F(102,DIM),ZP(100),    *002
               0 SPRK,IPRK,LPRK,FVA,FVB,STATED,HYDRK,PENNSY,SUZ(11)             *002
                VECTOR VALUES DIM = 2,1,51                                      *003
                INTEGER H,I,K,S,GAP                                             *004
                ENTRY TO FEC.                                                   *005
                HZ=P                                                            *006
                K=S                                                             *007
                H=GAP                                                           *008
                WHENEVER HZ.GE.D(K)                                             *009
                   TRANSFER TO MADRID                                           *010
                OR WHENEVER HZ.GE.R(K)                                          *011
                   WETP=2.*R(K)*(3.14159-ARCCOS.((HZ-R(K))/R(K)))               *012
                OR WHENEVER HZ.L.R(K)                                           *013
                   WETP=2.*R(K)*ARCCOS.((R(K)-HZ)/R(K))                         *014
                END OF CONDITIONAL                                              *015
                A=PFPA.(HZ,K)                                                   *016
                HYDRAD=A/WETP                                                   *017
                REY=HYDRAD*4.*.ABS.V/NU                                         *018
                TRANSFER TO LAPAZ                                               *019
MADRID          REY=D(K)*.ABS.V/NU                                              *020
LAPAZ           WHENEVER REY.L.64.                                              *021
                   W = 1.                                                       *022
                OR WHENEVER REY.L.100.                                          *023
                   W = 64./REY                                                  *024
                OR WHENEVER REY.L.3510C.                                        *025
                   X = REY-1CC.                                                 *026
                   I = X/H                                                      *027
                   ETA = (X-H*I)/H                                              *028
                   WHENEVER I.E.0                                               *029
                      I = 1                                                     *030
                      ETA = ETA - 1.                                            *031
                   END OF CONDITIONAL                                           *032
                   W=F(K,I)+(ETA/2.)*(F(K,I+1)-F(K,I-1))+(ETA/2.)*ETA*(F(K,I+   *033
               C    1)+F(K,I-1)-2.*F(K,I))                                      *033
                OR WHENEVER REY.GE.35100..AND.K.G.1                             *034
                   W = .C247                                                    *035
                OTHERWISE                                                       *036
                   W = .C324                                                    *037
                END OF CONDITIONAL                                              *038
                WHENEVER HZ.GE.D(K)                                             *039
                   FUNCTION RETURN W                                            *040
                OTHERWISE                                                       *041
                   WW=W/(8.*HYDRAD)                                             *042
                   FUNCTION RETURN WW                                           *043
                END OF CONDITIONAL                                              *044
                END OF FUNCTION                                                 *045
```

```
$ COMPILE MAD ,PRINT OBJECT,EXECUTE,DUMP,PUNCH OBJECT          SIMPQ.01          070218   04/04/64      9 12 43.3 AM

MAD (12 MAR 1964 VERSION) PROGRAM LISTING ... ... ...

                EXTERNAL FUNCTION (L,M,NN)                                          *001
                INTEGER N,IK,LK,K,NN,GAP,J,L                                        *002
                STATEMENT LABEL SATURN,APOLLO,AGENA                                 *003
                PROGRAM COMMON R(2),XI,D(2),PAREA,NC,GAP,F(102,DIM),ZP(100),        *004
               0 SPRK,IPRK,LPRK,FVA,FVB,STATED,NYORK,PENNSY,SUZ(11)                 *004
                VECTOR VALUES DIM = 2,1,51                                          *005
                ENTRY TO SIMPQ.                                                     *006
                J=L                                                                 *007
                N=NN                                                                *008
                MM=M                                                                *009
                AEVEN=0.                                                            *010
                AODD=0.                                                             *011
                OAA=PAREA-PFPA.(ZP(0),J)                                            *012
                NAA=PAREA-PFPA.(ZP(N),J)                                            *013
                WHENEVER N/2.E.(N-1)/2                                              *014
                  SATURN=APOLLO                                                     *015
                  K=1                                                               *016
                  MM=MM*0.5                                                         *017
                OTHERWISE                                                           *018
                  SATURN=AGENA                                                      *019
                  K=2                                                               *020
                END OF CONDITIONAL                                                  *021
                THROUGH THOR,FOR LK=K,K,LK.G.N-1                                    *022
                  AAAA=PAREA-PFPA.(ZP(LK),J)                                        *023
THOR            AEVEN=AEVEN+AAAA                                                    *024
                THROUGH ZEUS,FOR IK=1,K,IK.G.N                                      *025
                  TRANSFER TO SATURN                                                *026
APOLLO            ZA=(ZP(IK-1)+ZP(IK))*0.5                                          *027
                  TRANSFER TO PLUTO                                                 *028
AGENA             ZA=ZP(IK)                                                         *029
PLUTO             BBBB=PAREA-PFPA.(ZA,J)                                            *030
ZEUS              AODD=AODD+BBBB                                                    *031
                V=(MM/3.)*(OAA+NAA+4.*AODD+2.*AEVEN)                                *032
                FUNCTION RETURN V                                                   *033
                END OF FUNCTION                                                     *034
```

MAD (12 MAR 1964 VERSION) PROGRAM LISTING ... ...

```
                EXTERNAL FUNCTION (A,L)                                          *001
                PROGRAM COMMON R(2),XI,D(2),PAREA,NU,GAP,F(102,DIM),ZP(100),     *002
              0 SPRK,IPRK,LPRK,FVA,FVB,STATED,NYORK,PENNSY,SUZ(11)               *002
                VECTOR VALUES DIM = 2,1,51                                       *003
                DIMENSION KK(10),XX(10),AA(10)                                   *004
                INTEGER J,L,I,GAP                                                *005
                ENTRY TO PARVOL.                                                 *006
                K=A                                                              *007
                J=L                                                              *008
                X=PARLEN.(K,J)                                                   *009
                DELX=X/10.                                                       *010
                AODD=0.                                                          *011
                AEVEN=0.                                                         *012
                THROUGH YUKON,FOR I=0,1,I.G.10                                   *013
                  XX(I)=DELX*I                                                   *014
                  KK(I)=PARK.(XX(I),J)                                           *015
                  AA(I)=PAREA-PFPA.(KK(I)+R(J),J)                                *016
                  WHENEVER I/2.E.(I-1)/2.AND.I.NE.0                              *017
                     AODD=AODD+AA(I)                                             *018
                  OR WHENEVER I.NE.0.AND.I.NE.10                                 *019
                     AEVEN=AEVEN+AA(I)                                           *020
YUKON             END OF CONDITIONAL                                             *021
                V=(DELX/3.)*(AA(0)+4.*AODD+2.*AEVEN+AA(10))                      *022
                FUNCTION RETURN V                                                *023
                END OF FUNCTION                                                  *024
```

MAD (12 MAR 1964 VERSION) PROGRAM LISTING ... ...

```
      EXTERNAL FUNCTION (H,I,L)                                          *001
      INTEGER MK,I                                                       *002
      PROGRAM COMMON R(2),XI,D(2),PAREA,NU,GAP,F(102,DIM),ZP(100),       *003
     0 SPRK,IPRK,LPRK,FVA,FVB,STATED,NYGRK,PENNSY,SUZ(11)                *003
      VECTOR VALUES DIM = 2,1,51                                         *004
      ENTRY TO PINTRP.                                                   *005
      X=L                                                                *006
      MK=I                                                               *007
      DELXC=H                                                            *008
      TH=(X/DELXC)                                                       *009
      WHENEVER MK.E.0                                                    *010
        MK=1                                                             *011
        TH=TH-1.                                                         *012
      END OF CONDITIONAL                                                 *013
      Z=ZP(MK)+(TH/2.)*(ZP(MK+1)-ZP(MK-1))+TH*TH*.5*(ZP(MK+1)+ZP(M       *014
     0 K-1)-2.*ZP(MK))                                                   *014
      FUNCTION RETURN Z                                                  *015
      END OF FUNCTION                                                    *016
```

MAD (12 MAR 1964 VERSION) PROGRAM LISTING ... ...

```
                EXTERNAL FUNCTION (H,I,M,K,YE)                                    *001
                INTEGER J,K,MK,I,IMK,HK                                           *002
                STATEMENT LABEL SUN,EARTH,URANUS                                  *003
                PROGRAM COMMON R(2),XI,D(2),PAREA,NU,GAP,F(102,DIM),ZP(100),      *004
              0 SPRK,IPRK,LPRK,FVA,FVB,STATED,NYORK,PENNSY,SUZ(11)                *004
                VECTOR VALUES DIM = 2,1,51                                        *005
                ENTRY TO SIMPWV.                                                  *006
                DELXC=H                                                           *007
                MK=I                                                              *008
                NX=M                                                              *009
                J=K                                                               *010
                YY=YE                                                             *011
                WHENEVER NX.LE.0.,FUNCTION RETURN 0.                              *012
                IMK=((NX+YY)/DELXC)+1.                                            *013
                XX=IMK*DELXC-(NX+YY)                                              *014
                ZZZ=PINTRP.(DELXC,MK-IMK,XX)                                      *015
                ZZ=PINTRP.(DELXC,MK-1,DELXC-YY)                                   *016
                AODD=0.                                                           *017
                AEVEN=0.                                                          *018
                XYX=XX                                                            *019
                THROUGH JUPTER,FOR HK=1,1,HK.G.9                                  *020
                  XYX=XYX+(NX/10.)                                                *021
                  WHENEVER XYX.G.DELXC                                            *022
                      IMK=IMK-1                                                   *023
                      XYX=XYX-DELXC                                               *024
                  END OF CONDITIONAL                                              *025
                  Z=PINTRP.(DELXC,MK-IMK,XYX)                                     *026
                  WHENEVER (HK+1)/2.E.HK/2                                        *027
                     SUN=EARTH                                                    *028
                  OTHERWISE                                                       *029
                     SUN=URANUS                                                   *030
                  END OF CONDITIONAL                                              *031
                  TRANSFER TO SUN                                                 *032
EARTH             AAAA=PAREA-PFPA.(Z,J)                                           *033
                  AEVEN=AEVEN+AAAA                                                *034
                  TRANSFER TO JUPTER                                              *035
URANUS            BBBB=PAREA-PFPA.(Z,J)                                           *036
                  AODD=AODD+BBBB                                                  *037
JUPTER            CONTINUE                                                        *038
                OAA=PAREA-PFPA.(ZZZ,J)                                            *039
                NAA=PAREA-PFPA.(ZZ,J)                                             *040
                V=(NX/30.)*(OAA+4.*AODD+2.*AEVEN+NAA)                             *041
                FUNCTION RETURN V                                                 *042
                END OF FUNCTION                                                   *043
```

MAD (12 MAR 1964 VERSION) PROGRAM LISTING ... ...

```
      EXTERNAL FUNCTION (M)                                                *001
      INTEGER M,MK,SPRK,IPRK,LPRK,FVA,FVB                                  *002
      STATEMENT LABEL STATED,PENNSY,NYORK                                  *003
      PROGRAM COMMON R(2),XI,D(2),PAREA,NU,GAP,F(102,DIM),ZP(100),         *004
     0 SPRK,IPRK,LPRK,FVA,FVB,STATED,NYORK,PENNSY,SUZ(11)                  *004
      VECTOR VALUES DIM = 2,1,51                                           *005
      FORMAT VARIABLE FVA,FVB                                              *006
      ENTRY TO PRTLAW.                                                     *007
      MK=M                                                                 *008
      WHENEVER MK.LE.14                                                    *009
        SPRK = 0                                                           *010
        IPRK = 1                                                           *011
        LPRK = MK                                                          *012
        FVA = MK                                                           *013
        FVB = MK+1                                                         *014
        STATED = NYORK                                                     *015
      OR WHENEVER MK.G.14.AND.MK.LE.29                                     *016
        SPRK = 0                                                           *017
        IPRK = 1                                                           *018
        LPRK = 14                                                          *019
        FVA = 14                                                           *020
        FVB = 15                                                           *021
        STATED = PENNSY                                                    *022
      OR WHENEVER MK.G.29.AND.MK.LE.44                                     *023
        SPRK = 0                                                           *024
        IPRK = 2                                                           *025
        LPRK = 28                                                          *026
        FVA = 14                                                           *027
        FVB = 15                                                           *028
        STATED = PENNSY                                                    *029
      OR WHENEVER MK.G.44.AND.MK.LE.59                                     *030
        SPRK = 0                                                           *031
        IPRK = 3                                                           *032
        LPRK = 42                                                          *033
        FVA = 14                                                           *034
        FVB = 15                                                           *035
        STATED = PENNSY                                                    *036
      OR WHENEVER MK.G.59.AND.MK.LE.74                                     *037
        SPRK = 0                                                           *038
        IPRK = 4                                                           *039
        LPRK = 56                                                          *040
        FVA = 14                                                           *041
        FVB = 15                                                           *042
        STATED = PENNSY                                                    *043
      OR WHENEVER MK.G.74.AND.MK.LE.89                                     *044
        SPRK = 0                                                           *045
        IPRK = 5                                                           *046
        LPRK = 70                                                          *047
        FVA = 14                                                           *048
        FVB = 15                                                           *049
        STATED = PENNSY                                                    *050
      END OF CONDITIONAL                                                   *051
      TRANSFER TO SCRIBE                                                   *052
```

```
      ENTRY TO PRTRUL.
      MK = M
      WHENEVER MK.G.14.AND.MK.LE.29
        SPRK = 15
        IPRK = 1
        LPRK = MK
        FVA = MK-15
        FVB = MK-14
        STATED = NYORK
      OR WHENEVER MK.G.29.AND.MK.LE.44
        SPRK = 30
        IPRK = 1
        LPRK = MK
        FVA = MK-30
        FVB = MK-29
        STATED = NYORK
      OR WHENEVER MK.G.44.AND.MK.LE.59
        SPRK = 45
        IPRK = 1
        LPRK = MK
        FVA = MK-45
        FVB = MK-44
        STATED = NYORK
      OR WHENEVER MK.G.59.AND.MK.LE.74
        SPRK = 60
        IPRK = 1
        LPRK = MK
        FVA = MK-60
        FVB = MK-59
        STATED = NYORK
      OR WHENEVER MK.G.74.AND.MK.LE.89
        SPRK = 75
        IPRK = 1
        LPRK = MK
        FVA = MK-75
        FVB = MK-74
        STATED = NYORK
      END OF CONDITIONAL
SCRIBE CONTINUE
      FUNCTION RETURN
      END OF FUNCTION
```

```
$ COMPILE MAD, PRINT OBJECT, EXECUTE, DUMP, PUNCH OBJECT        USURG.01        070219   04/04/64      9 13 15.7 AM

MAD (12 MAR 1964 VERSION) PROGRAM LISTING ... ... ...

                EXTERNAL FUNCTION (Q,L)                                                  *001
                INTEGER I,J,L                                                            *002
                PROGRAM COMMON R(2),XI,D(2),PAREA,NU,GAP,F(102,DIM),ZP(100),             *003
              0 SPRK,IPRK,LPRK,FVA,FVB,STATED,NYORK,PENNSY,SUZ(11)                       *003
                VECTOR VALUES DIM = 2,1,51                                               *004
                ENTRY TO USURG.                                                          *005
                J=L                                                                      *006
                Z=Q                                                                      *007
                DEL=D(J)/10.                                                             *008
MEXICO          THROUGH MEXICO,FOR I=0,1,DEL*(I+1).G.Z                                   *009
                TH=Z-DEL*I                                                               *010
                WHENEVER I.E.0                                                           *011
                  I=1                                                                    *012
                  TH=TH-1.                                                               *013
                END OF CONDITIONAL                                                       *014
                U=SUZ(I)+(TH/2.)*(SUZ(I+1)-SUZ(I-1))+TH*TH*5.*(SUZ(I+1)+                 *015
              0 SUZ(I-1)-2.*SUZ(I))                                                      *015
                COEFF=2.*SQRT.(64.32*R(J))                                               *016
                FUNCTION RETURN U*COEFF                                                  *017
                END OF FUNCTION                                                          *018
```

APPENDIX III

EXPERIMENTAL DATA; RUNS NUMBERS 25 and 34

The experimental data obtained in the laboratory from Runs Numbers 25 and 34 (Group II conditions) are presented in tabular form in this appendix. Tables I and II give the pressure-rise data at the gate valve and column-separation void data, respectively, for Run Number 25. Tables III and IV provide the corresponding data for Run Number 34. Time is referenced to the moment of valve closure. Head in feet of water is measured with respect to absolute pressure conditions.

TABLE I

EXPERIMENTAL RUN NUMBER 25
PRESSURE-RISE DATA AT GATE VALVE

Time Seconds	Head Feet of Water	Time Seconds	Head Feet of Water
.0012	17.3	.1362	314.5
.0073	135.8	.1382	319.9
.0110	180.7	.1421	308.7
.0134	235.4	.1444	308.4
.0147	248.9	.1478	295.8
.0166	259.8	.1526	291.4
.0187	255.7	.1559	281.2
.0194	269.7	.1588	282.2
.0212	278.8	.1650	272.7
.0247	267.3	.1685	275.4
.0276	280.2	.1713	268.6
.0294	280.2	.1738	269.3
.0324	275.4	.1803	260.6
.0359	291.1	.1828	263.2
.0379	295.5	.1869	255.7
.0410	286.3	.1912	258.5
.0447	297.2	.1974	248.9
.0494	283.2	.1991	242.8
.0507	290.4	.2007	237.7
.0532	291.1	.2185	41.8
.0560	283.6	.2201	31.2
.0596	294.8	.2235	13.8
.0615	293.1	.2276	11.3
.0625	285.3	--	--
.0643	280.2	2.0524	11.3
.0667	283.2	2.0568	76.4
.0694	285.6	2.0581	67.2
.0721	282.9	2.0599	83.5
.0746	288.0	2.0631	32.9
.0769	287.3	2.0663	11.3
.0795	299.2	2.0718	16.8
.0828	295.1	2.1155	16.1
.0846	303.3	2.1188	28.2
.0868	306.7	2.1218	87.3
.0938	305.0	2.1233	111.1
.0997	310.4	2.1250	126.7
.1032	313.5	2.1259	120.2
.1079	324.3	2.1280	43.1
.1106	320.3	2.1302	83.9
.1149	327.0	2.1306	146.4
.1200	318.6	2.1324	130.1
.1221	324.7	2.1331	155.2
.1266	313.5	2.1365	119.9
.1307	319.6	2.1387	152.8

TABLE I (Cont'd)

Time Seconds	Head Feet of Water	Time Seconds	Head Feet of Water
2.1400	153.2	2.3031	151.5
2.4112	148.8	2.3080	153.6
2.1443	166.4	2.3103	152.8
2.1478	149.4	2.3118	160.9
2.1509	171.5	2.3147	165.1
2.1530	171.5	2.3178	165.1
2.1558	161.7	2.3213	154.5
2.1593	174.2	2.3374	47.9
2.1625	168.8	2.3427	34.3
2.1660	174.9	2.3488	15.5
2.1703	169.1	2.3565	11.3
2.1744	177.6	--	--
2.1777	165.7	3.3303	11.3
2.1799	169.1	3.3344	81.1
2.1821	165.7	3.3358	68.9
2.1843	167.4	3.3376	77.8
2.1865	164.0	3.3384	65.5
2.1887	174.6	3.3416	50.9
2.1909	168.6	3.3434	84.9
2.1933	174.2	3.3466	90.3
2.1958	187.8	3.3500	80.5
2.1990	182.7	3.3528	76.8
2.2024	195.3	3.3591	111.4
2.2056	188.5	3.3619	110.7
2.2088	198.0	3.3656	126.3
2.2122	188.8	3.3704	115.8
2.2159	199.4	3.3735	123.3
2.2196	198.0	3.3766	120.6
2.2230	206.5	3.3804	125.3
2.2277	201.4	3.3851	119.8
2.2312	204.7	3.3895	123.3
2.2365	202.8	3.3988	118.4
2.2391	208.2	3.4026	126.3
2.2431	202.4	3.4068	126.3
2.2449	207.5	3.4103	130.7
2.2494	206.5	3.4148	133.1
2.2537	209.2	3.4179	138.5
2.2579	208.5	3.4210	136.4
2.2609	199.4	3.4242	141.5
2.2641	201.4	3.4285	140.9
2.2681	194.9	3.4309	143.7
2.2718	196.1	3.4347	143.7
2.2750	189.9	3.4385	150.3
2.2836	191.2	3.4413	148.3
2.2879	185.8	3.4450	149.3
2.2924	174.9	3.4492	140.9

TABLE I (Cont'd)

Time Seconds	Head Feet of Water	Time Seconds	Head Feet of Water
3.4556	140.2	4.4582	109.0
3.4685	140.2	4.4651	109.7
3.4719	142.6	4.4697	112.4
3.4762	136.4	4.4790	112.1
3.4834	130.7	4.4883	104.6
3.4890	130.3	4.5000	86.3
3.4982	130.0	4.5082	108.0
3.5062	132.4	4.5184	100.9
3.5100	131.3	4.5296	85.9
3.5179	123.2	4.5365	81.5
3.5222	125.3	4.5415	83.5
3.5281	124.9	4.5481	75.1
3.5344	123.2	4.5593	49.6
3.5379	116.4	4.5678	41.8
3.5485	70.3	4.5785	35.7
3.5566	47.2	4.5932	29.5
3.5628	35.0	4.6214	21.8
3.5770	30.2	4.6644	14.4
3.6048	11.3	4.6663	11.3
--	--		
4.3460	11.3		
4.3506	62.8		
4.3519	67.6		
4.3535	76.8		
4.3566	79.1		
4.3596	83.2		
4.3623	84.2		
4.3653	66.3		
4.3675	89.3		
4.3732	93.1		
4.3776	92.0		
4.3826	96.1		
4.3863	94.8		
4.3898	99.5		
4.3954	86.1		
4.3987	98.2		
4.4009	95.1		
4.4043	99.2		
4.4076	96.1		
4.4112	101.5		
4.4117	104.9		
4.4216	103.6		
4.4251	107.7		
4.4335	102.9		
4.4419	106.3		
4.4460	110.7		

TABLE II

EXPERIMENTAL RUN NUMBER 25
COLUMN-SEPARATION VOID DATA

Time Seconds	Depth of Flow -- Feet Gage No. 1	Gage No. 2	Gage No. 4	Time Seconds	Depth of Flow -- Feet Gage No. 1	Gage No. 2	Gage No. 4
0.00	.083	.083	.083	1.10	.052	.066	.083
0.20	.083	.083	.083	.12	.052	.065	.083
0.30	.083	.083	.083	.14	.051	.064	.083
.32	.081	.083	.083	.16	.051	.064	.081
.34	.082	.083	.083	.18	.050	.064	.076
.36	.081	.083	.083	1.20	.050	.064	.069
.38	.080	.083	.083	.22	.049	.062	.062
0.40	.079	.083	.083	.24	.049	.060	.054
.42	.079	.083	.083	.26	.048	.060	.051
.44	.078	.080	.083	.28	.047	.060	.055
.46	.076	.078	.083	1.30	.047	.061	.065
.48	.075	.074	.083	.32	.048	.063	.064
0.50	.073	.071	.083	.34	.048	.065	.060
.52	.071	.068	.083	.36	.049	.068	.057
.54	.069	.067	.083	.38	.050	.067	.058
.56	.067	.070	.083	1.40	.051	.065	.062
.58	.064	.075	.083	.42	.052	.064	.064
0.60	.062	.069	.083	.44	.053	.063	.063
.62	.059	.067	.083	.46	.053	.064	.062
.64	.057	.063	.083	.48	.053	.065	.060
.66	.058	.055	.083	1.50	.052	.065	.056
.68	.060	.052	.083	.52	.051	.067	.054
0.70	.058	.050	.083	.54	.050	.068	.053
.72	.057	.051	.083	.56	.049	.069	.054
.74	.055	.052	.083	.58	.048	.068	.054
.76	.052	.056	.083	1.60	.048	.068	.055
.78	.050	.056	.083	.62	.048	.067	.055
0.80	.050	.053	.083	.64	.048	.064	.056
.82	.050	.056	.083	.66	.048	.062	.058
.84	.049	.056	.083	.68	.048	.062	.059
.86	.049	.059	.083	1.70	.049	.063	.060
.88	.050	.058	.083	.72	.050	.062	.061
0.90	.050	.061	.083	.74	.049	.062	.064
.92	.052	.062	.083	.76	.050	.063	.073
.94	.052	.069	.083	.78	.051	.065	.083
.96	.053	.070	.083	1.80	.051	.064	.083
.98	.053	.071	.083	.82	.050	.064	.083
1.00	.052	.071	.083	.84	.050	.069	.083
.02	.053	.071	.083	.86	.050	.075	.083
.04	.054	.068	.083	.88	.057	.083	.083
.06	.053	.067	.083	1.90	.079	.083	.083
.08	.052	.066	.083	.92	.081	.083	.083

TABLE II (Cont'd)

Time Seconds	Depth of Flow -- Feet Gage No. 1	Gage No. 2	Gage No. 4	Time Seconds	Depth of Flow -- Feet Gage No. 1	Gage No. 2	Gage No. 4
.94	.083	.083	.083	3.50	.083	.083	.083
.96	.083	.083	.083	5.00	.083	.083	.083
.98	.083	.083	.083				
2.00	.083	.083	.083				
2.10	.083	.083	.083				
2.20	.083	.083	.083				
2.30	.083	.083	.083				
2.40	.083	.083	.083				
2.50	.083	.083	.083				
2.60	.083	.083	.083				
.62	.083	.083	.083				
.64	.083	.083	.083				
.66	.082	.083	.083				
.68	.080	.083	.083				
2.70	.078	.083	.083				
.72	.076	.083	.083				
.74	.074	.083	.083				
.76	.072	.083	.083				
.78	.070	.083	.083				
2.80	.066	.083	.083				
.82	.064	.083	.083				
.84	.063	.083	.083				
.86	.064	.083	.083				
.88	.064	.083	.083				
2.90	.067	.083	.083				
.92	.069	.083	.083				
.94	.070	.083	.083				
.96	.070	.083	.083				
.98	.069	.083	.083				
3.00	.068	.083	.083				
.02	.068	.083	.083				
.04	.068	.083	.083				
.06	.068	.083	.083				
.08	.070	.083	.083				
3.10	.073	.083	.083				
.12	.076	.083	.083				
.14	.079	.083	.083				
.16	.080	.083	.083				
.18	.079	.083	.083				
3.20	.078	.083	.083				
.22	.079	.083	.083				
.24	.081	.083	.083				
.26	.083	.083	.083				
.28	.083	.083	.083				
3.30	.083	.083	.083				
3.40	.083	.083	.083				

TABLE III

EXPERIMENTAL RUN NUMBER 34
PRESSURE-RISE DATA AT GATE VALVE

Time Seconds	Head Feet of Water	Time Seconds	Head Feet of Water
.0028	17.6	.1260	308.2
.0074	183.8	.1314	311.1
.0105	195.6	.1350	303.1
.0121	181.7	.1385	302.2
.0140	180.3	.1404	293.3
.0156	273.5	.1429	291.9
.0186	256.3	.1449	274.9
.0211	273.2	.1474	278.3
.0237	249.8	.1494	275.0
.0273	280.9	.1519	268.2
.0308	261.7	.1542	266.4
.0337	283.0	.1554	260.8
.0364	280.9	.1600	259.0
.0392	281.5	.1633	249.5
.0412	277.7	.1659	250.4
.0436	280.6	.1705	243.0
.0462	291.9	.1739	245.4
.0490	275.9	.1774	241.5
.0523	291.9	.1808	239.2
.0555	278.9	.1833	238.6
.0592	290.1	.1846	238.3
.0635	276.5	.1879	240.7
.0658	278.6	.1900	240.7
.0692	278.6	.1910	234.1
.0712	275.6	.1929	231.2
.0733	280.9	.1941	225.0
.0763	277.4	.1962	209.9
.0782	284.5	.2046	136.4
.0821	285.7	.2128	50.9
.0839	294.0	.2147	36.6
.0871	292.5	.2171	24.5
.0899	300.5	.2206	11.3
.0942	296.9	--	--
.0987	312.3	1.8818	11.3
.1016	305.2	1.8850	87.6
.1038	314.1	1.8873	47.0
.1071	311.1	1.8908	47.6
.1109	312.6	1.8961	120.2
.1154	321.2	1.8995	122.2
.1187	312.6	1.9005	133.5
.1210	317.0	1.9031	133.5

TABLE III (Cont'd)

Time Seconds	Head Feet of Water	Time Seconds	Head Feet of Water
1.9046	142.1	2.0921	83.7
1.9066	145.0	2.0969	60.9
1.9092	140.3	2.1046	39.6
1.9108	148.3	2.1149	24.5
1.9130	155.4	2.1303	11.3
1.9145	159.2	--	--
1.9168	156.3	2.9938	11.3
1.9256	163.1	2.9977	79.3
1.9290	167.8	3.0024	80.2
1.9315	166.6	3.0048	90.5
1.9336	169.9	3.0101	90.5
1.9354	167.5	3.0160	97.4
1.9380	166.0	3.0227	93.8
1.9484	159.5	3.0256	97.9
1.9569	161.9	3.0333	92.9
1.9572	166.0	3.0409	92.0
1.9642	172.0	3.0499	95.0
1.9687	169.6	3.0596	98.2
1.9735	167.5	3.0687	106.8
1.9780	175.2	3.0711	107.7
1.9800	172.9	3.0759	112.7
1.9858	183.8	3.0792	114.2
1.9879	182.6	3.0816	118.7
1.9944	190.9	3.0910	120.1
2.0021	188.2	3.0965	123.7
2.0043	190.0	3.1096	124.6
2.0159	192.7	3.1192	121.0
2.0232	189.1	3.1286	115.7
2.0264	181.4	3.1363	111.0
2.0321	72.0	3.1391	113.3
2.0341	72.6	3.1477	113.0
2.0400	167.0	3.1545	113.0
2.0446	164.3	3.1609	118.7
2.0497	162.2	3.1718	121.9
2.0539	160.0	3.1756	121.6
2.0585	154.8	3.1872	100.6
2.0611	148.3	3.2052	55.9
2.0640	141.5	3.2173	38.7
2.0676	134.7	3.2256	32.5
2.0719	133.5	3.2468	27.2
2.0752	133.5	3.2602	11.3
2.0775	133.5	--	--
2.0835	131.1	3.8050	11.3
2.0868	118.7	3.8056	16.5

TABLE III (Cont'd)

Time Seconds	Head Feet of Water	Time Seconds	Head Feet of Water
3.8274	11.3	4.0872	93.2
3.8582	11.3	4.0912	89.4
3.8659	20.9	4.0958	80.2
3.8723	45.5	4.0986	73.7
3.8813	29.8	4.0136	65.4
3.8864	50.6	4.1124	57.7
3.8942	44.9	4.1229	51.5
3.9009	63.6	4.1299	42.3
3.9069	59.4	4.1389	41.4
3.9095	66.9	4.1423	41.4
3.9208	73.1	4.1507	34.6
3.9232	71.3	4.1714	29.8
3.9262	67.4	4.1799	30.7
3.9282	68.0	4.1900	19.5
3.9303	71.6	4.1984	11.3
3.9344	76.0	--	--
3.9353	74.3	4.6409	11.3
3.9376	71.9	4.6426	16.9
3.9399	73.4	4.6567	24.5
3.9426	76.0	4.6759	14.8
3.9454	75.1	4.6785	27.0
3.9491	74.8	4.6939	35.8
3.9517	78.4	4.7003	47.3
3.9550	76.3	4.7144	44.0
3.9591	79.0	4.7208	50.9
3.9593	84.0	4.7516	57.1
3.9659	81.7	4.7580	64.5
3.9711	79.1	4.7772	66.6
3.9775	81.1	4.7875	70.4
3.9813	84.6	4.7958	73.1
3.9870	81.7	4.7982	70.7
3.9912	87.0	4.8018	71.9
3.9951	84.9	4.8057	72.5
4.0000	88.2	4.8105	73.7
4.0053	86.1	4.8151	71.9
4.0120	88.5	4.8208	74.8
4.0174	66.7	4.8239	74.3
4.0217	90.8	4.8303	75.5
4.0279	90.2	4.8342	78.1
4.0298	93.5	4.8469	82.0
4.0446	90.5	4.8531	80.2
4.0467	88.2	4.8627	80.2
4.0540	87.6	4.8799	79.3
4.0657	92.6	4.8913	74.8
4.0708	93.5	4.9009	71.9
4.0809	95.6	4.9113	72.5

TABLE III (Cont'd)

Time Seconds	Head Feet of Water	Time Seconds	Head Feet of Water
4.9156	70.1		
4.9210	62.4		
4.9318	55.3		
4.9432	50.0		
4.9515	44.6		
4.9613	44.6		
4.9675	41.1		
4.9762	40.5		
4.9878	36.7		
5.0000	19.8		
5.0118	27.8		
5.0285	25.4		
5.0439	18.0		
5.0618	13.0		
5.0740	11.3		

TABLE IV

EXPERIMENTAL RUN NUMBER 34
COLUMN-SEPARATION VOID DATA

Time Seconds	Depth of Flow -- Feet Gage No. 1	Gage No. 4	Gage No. 5	Time Seconds	Depth of Flow -- Feet Gage No. 1	Gage No. 4	Gage No. 5
0.00	.083	.083	.083	.98	.048	.079	.083
0.20	.083	.083	.083	1.00	.048	.073	.081
.22	.083	.083	.083	.02	.047	.065	.079
.24	.083	.083	.083	.04	.047	.054	.079
.26	.083	.083	.083	.06	.046	.051	.078
.28	.080	.083	.083	.08	.045	.050	.078
0.30	.078	.083	.083	1.10	.045	.056	.078
.32	.076	.083	.083	.12	.045	.067	.077
.34	.073	.083	.083	.14	.044	.063	.077
.36	.071	.083	.083	.16	.043	.057	.073
.38	.073	.083	.083	.18	.043	.053	.068
0.40	.076	.083	.083	1.20	.043	.053	.063
.42	.077	.083	.083	.22	.042	.052	.061
.44	.073	.083	.083	.24	.043	.052	.058
.46	.070	.083	.083	.26	.043	.053	.052
.48	.068	.083	.083	.28	.043	.055	.052
0.50	.064	.083	.083	1.30	.043	.058	.059
.52	.059	.083	.083	.32	.043	.064	.062
.54	.054	.083	.083	.34	.044	.063	.061
.56	.051	.083	.083	.36	.044	.062	.056
.58	.049	.083	.083	.38	.043	.057	.054
0.60	.049	.083	.083	1.40	.044	.058	.051
.62	.051	.083	.083	.42	.044	.054	.051
.64	.051	.083	.083	.44	.044	.052	.052
.66	.050	.083	.083	.46	.043	.050	.052
.68	.049	.083	.083	.48	.043	.046	.053
0.70	.048	.083	.083	1.50	.043	.049	.054
.72	.046	.083	.083	.52	.043	.049	.055
.74	.045	.083	.083	.54	.043	.054	.056
.76	.044	.083	.083	.56	.043	.054	.056
.78	.044	.083	.083	.58	.043	.052	.068
0.80	.043	.083	.083	1.60	.043	.054	.083
.82	.043	.083	.083	.62	.043	.055	.083
.84	.042	.083	.083	.64	.044	.058	.083
.86	.043	.083	.083	.66	.044	.072	.083
.88	.043	.083	.083	.68	.044	.083	.083
0.90	.044	.081	.083	1.70	.044	.083	.083
.92	.045	.081	.083	.72	.044	.083	.083
.94	.047	.081	.083	.74	.044	.083	.083
.96	.048	.080	.083	.76	.044	.083	.083

TABLE IV (Cont'd)

Time Seconds	Depth of Flow -- Feet Gage No. 1	No. 4	No. 5	Time Seconds	Depth of Flow -- Feet Gage No. 1	No. 4	No. 5
1.78	.044	.083	.083	.06	.079	.083	.083
1.80	.045	.083	.083	.08	.079	.083	.083
.82	.052	.083	.083	3.10	.082	.083	.083
.84	.071	.083	.083	.12	.083	.083	.083
.86	.081	.083	.083	.14	.083	.083	.083
.88	.083	.083	.083	.16	.083	.083	.083
1.90	.083	.083	.083	.18	.083	.083	.083
2.00	.083	.083	.083	3.20	.083	.083	.083
2.10	.083	.083	.083	3.30	.083	.083	.083
2.20	.083	.083	.083	3.40	.083	.083	.083
2.30	.083	.083	.083	3.50	.083	.083	.083
2.40	.083	.083	.083	5.00	.083	.083	.083
.42	.081	.083	.083				
.44	.079	.083	.083				
.46	.077	.083	.083				
.48	.075	.083	.083				
2.50	.074	.083	.083				
.52	.072	.083	.083				
.54	.070	.083	.083				
.56	.068	.083	.083				
.58	.063	.083	.083				
2.60	.057	.083	.083				
.62	.058	.083	.083				
.64	.060	.083	.083				
.66	.060	.083	.083				
.68	.061	.083	.083				
2.70	.063	.083	.083				
.72	.063	.083	.083				
.74	.063	.083	.083				
.76	.063	.083	.083				
.78	.063	.083	.083				
2.80	.063	.083	.083				
.82	.063	.083	.083				
.84	.064	.083	.083				
.86	.064	.083	.083				
.88	.065	.083	.083				
2.90	.065	.083	.083				
.92	.064	.083	.083				
.94	.064	.083	.083				
.96	.063	.083	.083				
.98	.063	.083	.083				
3.00	.063	.083	.083				
.02	.065	.083	.083				
.04	.069	.083	.083				

APPENDIX IV

COMPUTER SIMULATED RESULTS

The results obtained from digital computer simulation of column separation accompanying transient pipe flow for Group II laboratory conditions are presented in this appendix. Photo reduced copies of the line-printer output list the data in sequence with respect to time. However, only the first 2,000 cycles (3.704 seconds of the simulated phenomena) are presented.

Certain events which occur during the course of the simulation are of particular interest. These events are identified according to time and to cycle number:

Time in Seconds	Cycle No.	Event
0	-	Computation starts while steady-state conditions prevail.
.00557	3	Gate valve is instantaneously closed.
.10299	55	High pressure wave reaches reservoir; direction of flow at reservoir reverses.
.03711-.18557	-	At valve, pressure continues to increase slightly as pipe is "packed".
.19299	104	Direction of flow at valve reverses and pressure begins to decrease.
.20413	110	Negative absolute pressure occurs at gate valve and initial separation void forms. Free-surface flow throughout void is toward reservoir.

Time in Seconds	Cycle No.	Event
1.16723	629	Flow within void reverses direction at point 0.384 foot from gate valve. Reversal propagates in both directions from this point with subsequent cycles.
1.48270	799	Column separation void reaches its maximum extent, 2.30 + feet measured from gate valve, and hovers at this approximate distance.
1.62837	869	Flow direction at reservoir reverses. Flow starts toward valve.
2.11363	1139	Void starts to retreat from its maximum extent.
3.13426	1689	Initial void collapses. Second high pressure rise occurs.
3.23540	1743	High pressure wave reaches reservoir; direction of flow at reservoir reverses.
3.15468-3.32911	-	Pressure continues to increase at valve as pipe is "packed".
3.33468	1797	Negative absolute pressure occurs at the gate valve and the second separation voids forms.

GIVEN INFORMATION

GIVEN PHYSICAL DATA AND CONSTANTS
RHO = 1.930 KA = .4860E 08 VMAX = 3.50 HBAR = 33.224 Q = -.0107

DIMENSIONAL DATA DESCRIBING ANALYTIC MODEL
HEL = 34.719 MEL = 26.328 LEL = 22.078 WSEL = 22.574 LOC1 = 18.000 LOC2 = 44.000 LOC3 = 444.000

PIPE CHARACERISTICS AND RELATED DATA
E(1) = .5112E 08 ZETA(1) = .280 D(1) = .08278 B(1) = .06250 R(1) = .04139 LL(1) = 0.771 MN(1) = 1
E(2) = .2448E 10 ZETA(2) = .300 D(2) = .08292 B(2) = .04678 R(2) = .04146 LL(2) = 434.187 MN(2) = 50

PROGRAM OPERATION AND CONTROL DATA
MAXIMUM ALLOWABLE ITERATIONS = 4000 COMPUTATION CUTOFF LIMIT = 1600 INITIAL CAVITY PRINTOUT = 4 VALVE SHUTOFF POINT = 3
INITIAL PRINTOUT LIMIT POINT = 4 PRINTOUT FREQUENCY CONTROL = 10 CAVITY PRINTOUT CYCLE = 2

FRICTION VALUES FOR CONSECUTIVE REYNOLDS NUMBERS FROM 100 TO 35100 IN INCREMENTS OF 1000.

REYNOLDS NO. = 100	F(1, 0) = .7000	F(2, 0) = .6400
REYNOLDS NO. = 1100	F(1, 1) = .1400	F(2, 1) = .0865
REYNOLDS NO. = 2100	F(1, 2) = .0925	F(2, 2) = .0560
REYNOLDS NO. = 3100	F(1, 3) = .0735	F(2, 3) = .0445
REYNOLDS NO. = 4100	F(1, 4) = .0630	F(2, 4) = .0385
REYNOLDS NO. = 5100	F(1, 5) = .0570	F(2, 5) = .0350
REYNOLDS NO. = 6100	F(1, 6) = .0525	F(2, 6) = .0328
REYNOLDS NO. = 7100	F(1, 7) = .0490	F(2, 7) = .0318
REYNOLDS NO. = 8100	F(1, 8) = .0470	F(2, 8) = .0312
REYNOLDS NO. = 9100	F(1, 9) = .0454	F(2, 9) = .0311
REYNOLDS NO. = 10100	F(1,10) = .0438	F(2,10) = .0309
REYNOLDS NO. = 11100	F(1,11) = .0422	F(2,11) = .0306
REYNOLDS NO. = 12100	F(1,12) = .0412	F(2,12) = .0302
REYNOLDS NO. = 13100	F(1,13) = .0402	F(2,13) = .0299
REYNOLDS NO. = 14100	F(1,14) = .0393	F(2,14) = .0296
REYNOLDS NO. = 15100	F(1,15) = .0386	F(2,15) = .0292
REYNOLDS NO. = 16100	F(1,16) = .0380	F(2,16) = .0289
REYNOLDS NO. = 17100	F(1,17) = .0374	F(2,17) = .0287
REYNOLDS NO. = 18100	F(1,18) = .0368	F(2,18) = .0284
REYNOLDS NO. = 19100	F(1,19) = .0362	F(2,19) = .0280
REYNOLDS NO. = 20100	F(1,20) = .0357	F(2,20) = .0278
REYNOLDS NO. = 21100	F(1,21) = .0352	F(2,21) = .0275
REYNOLDS NO. = 22100	F(1,22) = .0348	F(2,22) = .0272
REYNOLDS NO. = 23100	F(1,23) = .0345	F(2,23) = .0270
REYNOLDS NO. = 24100	F(1,24) = .0342	F(2,24) = .0268
REYNOLDS NO. = 25100	F(1,25) = .0339	F(2,25) = .0266
REYNOLDS NO. = 26100	F(1,26) = .0337	F(2,26) = .0263
REYNOLDS NO. = 27100	F(1,27) = .0334	F(2,27) = .0261
REYNOLDS NO. = 28100	F(1,28) = .0332	F(2,28) = .0259
REYNOLDS NO. = 29100	F(1,29) = .0330	F(2,29) = .0257
REYNOLDS NO. = 30100	F(1,30) = .0329	F(2,30) = .0255
REYNOLDS NO. = 31100	F(1,31) = .0328	F(2,31) = .0253
REYNOLDS NO. = 32100	F(1,32) = .0327	F(2,32) = .0251
REYNOLDS NO. = 33100	F(1,33) = .0326	F(2,33) = .0249
REYNOLDS NO. = 34100	F(1,34) = .0325	F(2,34) = .0248
REYNOLDS NO. = 35100	F(1,35) = .0324	F(2,35) = .0247

COMPUTED RESULTS

COMPUTED VALUES OF RELATIVE PRESSURE HEAD, VELOCITY, ELEVATION, AND ANGLE OF PIPE INCLINATION AT TIME T = 0.

H(1, 0) = 46.246	V(1, 0) = -1.988	ELP(1, 0) = 34.719	THETA(1, 0) = .000
H(1, 1) = 46.491	V(1, 1) = -1.988	ELP(1, 1) = 34.719	THETA(1, 1) = .000
H(2, 0) = 46.491	V(2, 0) = -1.981	ELP(2, 0) = 34.719	THETA(2, 0) = .000
H(2, 1) = 46.677	V(2, 1) = -1.981	ELP(2, 1) = 34.719	THETA(2, 1) = .000
H(2, 2) = 46.863	V(2, 2) = -1.981	ELP(2, 2) = 32.028	THETA(2, 2) = .329
H(2, 3) = 47.049	V(2, 3) = -1.981	ELP(2, 3) = 29.193	THETA(2, 3) = .329
H(2, 4) = 47.236	V(2, 4) = -1.981	ELP(2, 4) = 26.358	THETA(2, 4) = .329
H(2, 5) = 47.422	V(2, 5) = -1.981	ELP(2, 5) = 26.236	THETA(2, 5) = .011
H(2, 6) = 47.608	V(2, 6) = -1.981	ELP(2, 6) = 26.142	THETA(2, 6) = .011
H(2, 7) = 47.794	V(2, 7) = -1.981	ELP(2, 7) = 26.049	THETA(2, 7) = .011
H(2, 8) = 47.980	V(2, 8) = -1.981	ELP(2, 8) = 25.956	THETA(2, 8) = .011
H(2, 9) = 48.166	V(2, 9) = -1.981	ELP(2, 9) = 25.862	THETA(2, 9) = .011
H(2, 10) = 48.352	V(2, 10) = -1.981	ELP(2, 10) = 25.769	THETA(2, 10) = .011
H(2, 11) = 48.539	V(2, 11) = -1.981	ELP(2, 11) = 25.676	THETA(2, 11) = .011
H(2, 12) = 48.725	V(2, 12) = -1.981	ELP(2, 12) = 25.582	THETA(2, 12) = .011
H(2, 13) = 48.911	V(2, 13) = -1.981	ELP(2, 13) = 25.489	THETA(2, 13) = .011
H(2, 14) = 49.097	V(2, 14) = -1.981	ELP(2, 14) = 25.396	THETA(2, 14) = .011
H(2, 15) = 49.283	V(2, 15) = -1.981	ELP(2, 15) = 25.302	THETA(2, 15) = .011
H(2, 16) = 49.469	V(2, 16) = -1.981	ELP(2, 16) = 25.209	THETA(2, 16) = .011
H(2, 17) = 49.655	V(2, 17) = -1.981	ELP(2, 17) = 25.116	THETA(2, 17) = .011
H(2, 18) = 49.841	V(2, 18) = -1.981	ELP(2, 18) = 25.022	THETA(2, 18) = .011
H(2, 19) = 50.028	V(2, 19) = -1.981	ELP(2, 19) = 24.929	THETA(2, 19) = .011
H(2, 20) = 50.214	V(2, 20) = -1.981	ELP(2, 20) = 24.836	THETA(2, 20) = .011
H(2, 21) = 50.400	V(2, 21) = -1.981	ELP(2, 21) = 24.742	THETA(2, 21) = .011
H(2, 22) = 50.586	V(2, 22) = -1.981	ELP(2, 22) = 24.649	THETA(2, 22) = .011
H(2, 23) = 50.772	V(2, 23) = -1.981	ELP(2, 23) = 24.556	THETA(2, 23) = .011
H(2, 24) = 50.958	V(2, 24) = -1.981	ELP(2, 24) = 24.462	THETA(2, 24) = .011
H(2, 25) = 51.144	V(2, 25) = -1.981	ELP(2, 25) = 24.369	THETA(2, 25) = .011
H(2, 26) = 51.331	V(2, 26) = -1.981	ELP(2, 26) = 24.276	THETA(2, 26) = .011
H(2, 27) = 51.517	V(2, 27) = -1.981	ELP(2, 27) = 24.182	THETA(2, 27) = .011
H(2, 28) = 51.703	V(2, 28) = -1.981	ELP(2, 28) = 24.089	THETA(2, 28) = .011
H(2, 29) = 51.889	V(2, 29) = -1.981	ELP(2, 29) = 23.996	THETA(2, 29) = .011
H(2, 30) = 52.075	V(2, 30) = -1.981	ELP(2, 30) = 23.902	THETA(2, 30) = .011
H(2, 31) = 52.261	V(2, 31) = -1.981	ELP(2, 31) = 23.809	THETA(2, 31) = .011
H(2, 32) = 52.447	V(2, 32) = -1.981	ELP(2, 32) = 23.716	THETA(2, 32) = .011
H(2, 33) = 52.634	V(2, 33) = -1.981	ELP(2, 33) = 23.623	THETA(2, 33) = .011
H(2, 34) = 52.820	V(2, 34) = -1.981	ELP(2, 34) = 23.529	THETA(2, 34) = .011
H(2, 35) = 53.006	V(2, 35) = -1.981	ELP(2, 35) = 23.436	THETA(2, 35) = .011
H(2, 36) = 53.192	V(2, 36) = -1.981	ELP(2, 36) = 23.343	THETA(2, 36) = .011
H(2, 37) = 53.378	V(2, 37) = -1.981	ELP(2, 37) = 23.249	THETA(2, 37) = .011
H(2, 38) = 53.564	V(2, 38) = -1.981	ELP(2, 38) = 23.156	THETA(2, 38) = .011
H(2, 39) = 53.750	V(2, 39) = -1.981	ELP(2, 39) = 23.063	THETA(2, 39) = .011
H(2, 40) = 53.937	V(2, 40) = -1.981	ELP(2, 40) = 22.969	THETA(2, 40) = .011
H(2, 41) = 54.123	V(2, 41) = -1.981	ELP(2, 41) = 22.876	THETA(2, 41) = .011
H(2, 42) = 54.309	V(2, 42) = -1.981	ELP(2, 42) = 22.783	THETA(2, 42) = .011
H(2, 43) = 54.495	V(2, 43) = -1.981	ELP(2, 43) = 22.689	THETA(2, 43) = .011
H(2, 44) = 54.681	V(2, 44) = -1.981	ELP(2, 44) = 22.596	THETA(2, 44) = .011
H(2, 45) = 54.867	V(2, 45) = -1.981	ELP(2, 45) = 22.503	THETA(2, 45) = .011
H(2, 46) = 55.053	V(2, 46) = -1.981	ELP(2, 46) = 22.409	THETA(2, 46) = .011
H(2, 47) = 55.240	V(2, 47) = -1.981	ELP(2, 47) = 22.316	THETA(2, 47) = .011
H(2, 48) = 55.426	V(2, 48) = -1.981	ELP(2, 48) = 22.223	THETA(2, 48) = .011
H(2, 49) = 55.612	V(2, 49) = -1.981	ELP(2, 49) = 22.129	THETA(2, 49) = .011
H(2, 50) = 55.798	V(2, 50) = -1.981	ELP(2, 50) = 22.078	THETA(2, 50) = .000

VALUES OF KEY VARIABLES USED THROUGHOUT THE COMPUTATIONS IN PART I.

A(1) = 2449.848175, A(2) = 4729.905945, DELX(1) = 8.771030, DELX(2) = 8.783710

DELTT(1) = 3.575114E-03, DELTT(2) = 1.855691E-03, DELT = 1.855691E-03, MU(1) = 2.115712E-04

MU(2) = 2.112644E-04, CP(1) = .857193, CP(2) = .810101, AOG(1) = 76.176471

AOG(2) = 147.074190, GOA(1) = .013127, GOA(2) = 6.799289E-03

AT TIME T = .00186 SECONDS, AFTER 1 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	-1.9881	-1.9881	-1.9814	-1.9814	-1.9814	-1.9814	-1.9814	-1.9814
H	17.6737	17.9216	17.9216	22.0037	24.8080	27.6124	30.4168	33.1790

AT TIME T = .00371 SECONDS, AFTER 2 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	-1.9881	-1.9881	-1.9814	-1.9814	-1.9814	-1.9814	-1.9814	-1.9814
H	17.6738	17.9217	17.9217	22.0038	24.8082	27.6125	30.4169	33.1790

→ THE GATE VALVE AT LOCATION J = 1,I = 0 HAS BEEN INSTANTANEOUSLY CLOSED AT TIME T = .00557, SECONDS, OR AT OPERATION NUMBER 3. ←

AT TIME T = .00557 SECONDS, AFTER 3 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	.0000	-1.9881	-1.9814	-1.9814	-1.9814	-1.9814	-1.9814	-1.9814
H	169.1229	17.9218	17.9218	22.0039	24.8083	27.6127	30.4170	33.1790

AT TIME T = .01856 SECONDS, AFTER 10 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	.0000	-.2578	-.2569	-1.9814	-1.9814	-1.9814	-1.9814	-1.9814
H	277.4224	271.9850	271.9850	22.0053	24.8091	27.6135	30.4178	33.1790

AT TIME T = .03711 SECONDS, AFTER 20 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	.0000	-.0219	-.0218	-.2637	-1.9814	-1.9814	-1.9814	-1.9814
H	307.8768	307.4795	307.4795	275.0641	24.8108	27.6146	30.4178	33.1790

AT TIME T = .05567 SECONDS, AFTER 30 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	.0000	-.0040	-.0039	-.0282	-.2705	-1.9814	-1.9814	-1.9814
H	311.0562	311.0418	311.0418	310.6210	276.8696	27.6152	30.4179	33.1790

AT TIME T = .07423 SECONDS, AFTER 40 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	.0000	-.0026	-.0026	-.0103	-.0346	-.2773	-1.9814	-1.9814

H	312.1615	312.1759	312.1759	314.1866	312.4851	278.6736	30.4184	33.17[illegible]

AT TIME T = .09278 SECONDS, AFTER 60 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT TH
FLOW SYSTEM ARE AS TABULATED BELOW.

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	.0000	-.0025	-.0025	-.0089	-.0166	-.0409	-.2845	-1.9614
H	313.1086	313.1248	313.1248	315.3195	316.[illegible]518	314.3493	280.4785	33.1797

→ THE DIRECTION OF FLOW AT THE RESERVOIR END OF THE PIPE SYSTEM HAS REVERSED AT TIME T = .10299 SECONDS. ←

AT TIME T = .11134 SECONDS, AFTER 68 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT TH
FLOW SYSTEM ARE AS TABULATED BELOW.

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	.0000	-.0025	-.0025	-.0088	-.0152	-.0236	-.0473	1.4018
H	314.0418	314.0578	314.0578	316.2669	317.1845	317.9177	316.2143	33.1795

AT TIME T = .12990 SECONDS, AFTER 70 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT TH
FLOW SYSTEM ARE AS TABULATED BELOW.

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	.0000	-.0025	-.0024	-.0088	-.0151	-.0216	1.6579	1.8767
H	314.9730	314.9886	314.9886	317.1995	318.1314	319.0495	71.4492	33.1790

AT TIME T = .14846 SECONDS, AFTER 80 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE
FLOW SYSTEM ARE AS TABULATED BELOW.

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	.0000	-.0025	-.0024	-.0086	-.0151	1.6602	1.8964	1.9127
H	315.9036	315.9188	315.9188	318.1297	319.0628	72.4635	36.9225	33.1790

AT TIME T = .16701 SECONDS, AFTER 90 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE
FLOW SYSTEM ARE AS TABULATED BELOW.

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	.0000	-.0024	-.0024	-.0086	1.6611	1.8969	1.9147	1.9162
H	316.8337	316.8485	316.8485	319.0588	73.2625	37.8110	34.3139	33.1790

AT TIME T = .18557 SECONDS, AFTER 100 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE
FLOW SYSTEM ARE AS TABULATED BELOW.

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	.0000	-.0024	-.0024	1.6620	1.8973	1.9151	1.9164	1.9165
H	317.7625	317.7769	317.7769	74.0599	38.6820	35.1923	34.1157	33.1790

AT TIME T = .19485 SECONDS, AFTER 105 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE
FLOW SYSTEM ARE AS TABULATED BELOW.

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	.0000	1.2830	1.2786	1.8467	1.9115	1.9164	1.9168	1.9168
H	259.2695	220.2949	220.2949	47.0015	36.6331	35.0356	34.1033	33.1790

AT TIME T = .19870 SECONDS, AFTER 106 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE
FLOW SYSTEM ARE AS TABULATED BELOW.

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	.0000	1.4479	1.4430	1.8627	1.9126	1.9164	1.9167	1.9168
H	188.4125	177.1988	177.1988	44.6576	36.4565	35.0225	34.1024	33.1790

AT TIME T = .19856 SECONDS, AFTER 107 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	.0000	1.4354	1.4305	1.8751	1.9137	1.9166	1.9168	1.9169
H	125.4320	126.6930	126.6930	42.8510	36.3190	35.0116	34.1013	33.1790

AT TIME T = .20041 SECONDS, AFTER 108 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	.0000	1.3430	1.3385	1.8846	1.9144	1.9166	1.9168	1.9168
H	69.4124	76.2915	76.2915	41.4577	36.2138	35.0039	34.1008	33.1790

AT TIME T = .20227 SECONDS, AFTER 109 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	.0000	1.2163	1.2122	1.8920	1.9150	1.9168	1.9169	1.9169
H	19.9497	29.2550	29.2550	40.3820	36.1313	34.9972	34.1001	33.1790

→ COLUMN SEPARATION HAS OCCURRED AT THE GATE VALVE AT TIME T = .20413 SECONDS (OPERATION CYCLE NO. 110). THIS IS .19856 ← SECONDS AFTER CLOSURE OF THE GATE VALVE.

THE MAGNITUDE OF DELXC REMAINS THE MINIMUM VALUE.

GIVEN DATA AND COMPUTED VALUES PERTINENT TO COMPUTATION OF FLOW FOLLOWING COLUMN SEPARATION.

HVAPOR =	11.3000	DELXC =	.0640	DELTC =	.00928	MARK =	5	MUCH =	.1453
FACTOR =	5	XI =	.0250	INC =	90	IOTA =	.0001	PAREA =	.00538

THE INITIAL VELOCITIES AND DEPTHS IN THE VAPOR CAVITY ARE LISTED BELOW.

DIST.	.0000	.0640
LOC.	0	1
U	.000	1.053
Z	.061	.070

THE VELOCITIES AND ABSOLUTE HEADS THROUGHTOUT THE REMAINDER OF THE FULL-FLOWING PIPE SYSTEM ARE AS LISTED BELOW.

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	1.0935	1.2728	1.2685	1.8976	1.9154	1.9168	1.9169	1.9169
H	11.3000	15.5826	15.5826	39.5523	36.0688	34.9927	34.0998	33.1790

AT TIME T = .21155 SECONDS, AFTER 114 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.0640
LOC.	0	1
U	.000	.812
Z	.054	.066

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	1.3537	1.4227	1.4179	2.0872	1.9165	1.9170	1.9170	1.9170
H	11.3000	11.3000	11.3000	63.7753	35.9304	34.9820	34.0986	33.1790

AT TIME T = .22083 SECONDS, AFTER 119 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.0640	.1280
LOC.	0	1	2
U	.000	.635	1.296
Z	.051	.058	.067

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	1.4594	1.4696	1.4647	1.7330	1.9171	1.9173	1.9173	1.9173
H	11.3000	11.3000	11.3000	11.3000	35.8734	34.9768	34.0979	33.1790

AT TIME T = .23011 SECONDS, AFTER 124 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.0640	.1280	.1920
LOC.	0	1	2	3
U	.000	.543	1.120	1.501
Z	.048	.052	.058	.076

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	1.5011	1.5325	1.5273	1.7275	2.0926	1.9174	1.9174	1.9174
H	11.3000	11.3000	11.3000	11.3000	61.6408	34.9756	34.0981	33.1790

AT TIME T = .23938 SECONDS, AFTER 129 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.0640	.1280	.1920
LOC.	0	1	2	3
U	.000	.479	.988	1.328
Z	.046	.048	.053	.066

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	1.5418	1.5404	1.5352	1.7120	1.7491	1.9176	1.9176	1.9176
H	11.3000	11.3245	11.3245	11.3000	11.3000	34.9742	34.0977	33.1790

AT TIME T = .25794 SECONDS, AFTER 139 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.0640	.1280	.1920	.2560
LOC.	0	1	2	3	4
U	.000	.392	.798	1.082	1.304
Z	.042	.043	.046	.058	.069

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	1.5859	1.5839	1.5786	1.6978	1.7449	1.7555	1.9179	1.9179
H	11.3000	11.3867	11.3867	11.3000	11.3000	11.3000	34.0973	33.1790

AT TIME T = .27650 SECONDS, AFTER 149 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.0640	.1280	.1920	.2560	.3200
LOC.	0	1	2	3	4	5
U	.000	.333	.665	.897	1.142	1.453
Z	.039	.039	.042	.051	.060	.072

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	1.6156	1.6139	1.6085	1.6897	1.7400	1.7516	1.7618	1.9182
H	11.3000	11.3809	11.3809	11.3000	11.3000	11.3000	11.3000	33.1790

AT TIME T = .29505 SECONDS, AFTER 159 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.0640	.1280	.1920	.2560	.3200	.3840
LOC.	0	1	2	3	4	5	6
U	.000	.288	.564	.761	.979	1.227	1.475
Z	.036	.037	.039	.046	.054	.062	.072

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	1.6376	1.6361	1.6306	1.6855	1.7347	1.7478	1.7579	1.8718
H	11.3000	11.3676	11.3676	11.3000	11.3000	11.3000	11.3000	33.1790

AT TIME T = .31361 SECONDS, AFTER 169 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.0640	.1280	.1920	.2560	.3200	.3840	.4479
LOC.	0	1	2	3	4	5	6	7
U	.000	.252	.485	.657	.851	1.067	1.280	1.491
Z	.034	.035	.037	.043	.049	.055	.063	.074

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	1.6540	1.6527	1.6472	1.6839	1.7293	1.7440	1.7369	1.6356
H	11.3000	11.3574	11.3574	11.3000	11.3000	11.3000	13.8824	33.1790

AT TIME T = .33217 SECONDS, AFTER 179 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.0640	.1280	.1920	.2560	.3200	.3840	.4479	.5119
LOC.	0	1	2	3	4	5	6	7	8
U	.000	.221	.420	.573	.747	.942	1.131	1.319	1.504

Z	.032	.033	.035	.040	.045	.051	.057	.063	.074

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	1.6662	1.6652	1.6595	1.6845	1.7240	1.7276	1.6144	1.6527
H	11.3000	11.3472	11.3472	11.3000	11.3000	12.9934	30.4613	33.1790

AT TIME T = .35073 SECONDS, AFTER 189 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.0640	.1280	.1920	.2560	.3200	.3840	.4479	.5119	.5759
LOC.	0	1	2	3	4	5	6	7	8	9
U	.000	.194	.366	.504	.662	.839	1.012	1.187	1.335	1.675
Z	.031	.032	.034	.038	.042	.047	.052	.058	.065	.077

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	1.6753	1.6745	1.6688	1.6874	1.7145	1.6053	1.5940	1.5934
H	11.3000	11.3368	11.3368	11.3000	11.5560	29.4638	32.2588	33.1790

AT TIME T = .36928 SECONDS, AFTER 199 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.0640	.1280	.1920	.2560	.3200	.3840	.4479	.5119	.5759	.6399
LOC.	0	1	2	3	4	5	6	7	8	9	10
U	.000	.171	.321	.446	.591	.752	.912	1.074	1.212	1.440	1.682
Z	.030	.031	.033	.036	.040	.044	.049	.053	.060	.064	.078

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	1.6822	1.6815	1.6758	1.6923	1.5893	1.5816	1.5845	1.5853
H	11.3000	11.3295	11.3295	11.4256	27.4391	30.7421	32.2148	33.1790

AT TIME T = .38784 SECONDS, AFTER 209 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.0640	.1280	.1920	.2560	.3200	.3840	.4479	.5119	.5759	.6399
LOC.	0	1	2	3	4	5	6	7	8	9	10
U	.000	.150	.282	.396	.531	.679	.826	.977	1.108	1.309	1.446
Z	.029	.030	.032	.035	.038	.042	.046	.050	.055	.058	.066

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	1.6874	1.6868	1.6811	1.5880	1.5691	1.5687	1.5730	1.5756
H	11.3000	11.3215	11.3215	27.5549	29.2013	30.1870	31.7095	33.1790

AT TIME T = .40640 SECONDS, AFTER 219 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.0640	.1280	.1920	.2560	.3200	.3840	.4479	.5119	.5759	.6399	.7039
LOC.	0	1	2	3	4	5	6	7	8	9	10	11
U	.000	.131	.248	.354	.479	.615	.753	.892	1.018	1.203	1.316	1.358
Z	.028	.029	.031	.034	.037	.040	.043	.047	.052	.054	.061	.067

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	1.4891	1.4970	1.4919	1.5666	1.5675	1.5607	1.5599	1.5608
H	11.3000	12.4187	12.4187	29.1674	30.2893	30.1734	31.1983	33.1790

AT TIME T = .42495 SECONDS, AFTER 229 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.0640	.1280	.1920	.2560	.3200	.3840	.4479	.5119	.5759	.6399	.7039	.7679
LOC.	0	1	2	3	4	5	6	7	8	9	10	11	12
U	.000	.114	.219	.317	.434	.560	.688	.818	.939	1.112	1.212	1.272	1.297
Z	.028	.028	.030	.033	.035	.038	.041	.045	.049	.051	.057	.064	.073

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	1.4592	1.4587	1.4537	1.4719	1.5582	1.5588	1.5486	1.5444
H	11.3000	11.4113	11.4113	16.4861	30.0760	31.2951	31.6835	33.1790

AT TIME T = .44351 SECONDS, AFTER 239 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.0640	.1280	.1920	.2560	.3200	.3840	.4479	.5119	.5759	.6399	.7039	.7679
LOC.	0	1	2	3	4	5	6	7	8	9	10	11	12
U	.000	.100	.194	.285	.394	.512	.631	.752	.869	1.031	1.122	1.178	1.213
Z	.027	.028	.029	.032	.034	.037	.040	.043	.046	.048	.053	.060	.065

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	1.4495	1.4494	1.4446	1.4459	1.4637	1.5462	1.5434	1.5365
H	11.3000	11.3042	11.3042	13.7304	17.5533	31.5763	33.3069	33.1790

AT TIME T = .46207 SECONDS, AFTER 249 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.0640	.1280	.1920	.2560	.3200	.3840	.4479	.5119	.5759	.6399	.7039	.7679	.8319
LOC.	0	1	2	3	4	5	6	7	8	9	10	11	12	13
U	.000	.087	.171	.258	.359	.469	.581	.694	.807	.958	1.041	1.093	1.143	1.220
Z	.027	.027	.029	.031	.033	.035	.038	.041	.044	.046	.051	.057	.063	.066

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	1.4423	1.4422	1.4373	1.4365	1.4345	1.4489	1.5342	1.5423
H	11.3000	11.3037	11.3037	13.6583	15.2969	19.6201	33.1056	33.1790

AT TIME T = .48062 SECONDS, AFTER 259 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS

VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.0640	.1280	.1920	.2560	.3200	.3840	.4479	.5119	.5759	.6399	.7039	.7679	.8319	.8959
LOC.	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
U	.000	.076	.152	.233	.328	.430	.535	.642	.752	.892	.968	1.015	1.071	1.197	1.322
Z	.026	.027	.028	.030	.032	.034	.037	.039	.042	.044	.048	.054	.060	.063	.071

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	1.4342	1.4337	1.4288	1.4201	1.4218	1.4230	1.4483	1.5315
H	11.3000	11.3401	11.3401	14.1434	15.7289	16.8922	19.5991	33.1790

AT TIME T = .49918 SECONDS, AFTER 269 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.0640	.1280	.1920	.2560	.3200	.3840	.4479	.5119	.5759	.6399	.7039	.7679	.8319	.8959
LOC.	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
U	.000	.066	.134	.211	.300	.396	.495	.596	.702	.833	.962	.944	1.092	1.192	1.266
Z	.026	.027	.028	.029	.031	.033	.035	.038	.040	.042	.046	.052	.057	.061	.064

DIST.	.9599
LOC.	15
U	1.422
Z	.075

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	1.4224	1.4207	1.4159	1.4142	1.4147	1.4213	1.4212	1.3551
H	11.3000	11.4422	11.4422	14.6826	15.7351	15.7213	17.0824	33.1790

AT TIME T = .51774 SECONDS, AFTER 279 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.0640	.1280	.1920	.2560	.3200	.3840	.4479	.5119	.5759	.6399	.7039	.7679	.8319	.8959
LOC.	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
U	.000	.058	.120	.192	.275	.365	.458	.554	.657	.778	.841	.879	.937	1.078	1.130
Z	.026	.026	.027	.029	.031	.032	.034	.037	.039	.041	.045	.050	.055	.058	.061

DIST.	.9599
LOC.	15
U	1.266
Z	.065

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	1.4066	1.4053	1.4006	1.4046	1.4138	1.4129	1.3287	1.3115
H	11.3000	11.4560	11.4560	14.3098	14.6786	15.9303	29.2934	33.1790

AT TIME T = .53629 SECONDS, AFTER 289 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.0640	.1280	.1920	.2560	.3200	.3840	.4479	.5119	.5759	.6399	.7039	.7679	.8319	.8959
LOC.	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
U	.000	.091	.107	.174	.253	.337	.425	.517	.616	.727	.784	.820	.878	.956	1.066
Z	.026	.026	.027	.028	.030	.032	.033	.036	.038	.039	.043	.048	.053	.056	.058

DIST.	.9599	1.0239
LOC.	15	16
U	1.173	1.190
Z	.062	.068

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	1.3968	1.3961	1.3914	1.4002	1.4029	1.3216	1.3037	1.3024
H	11.3000	11.3402	11.3402	12.7375	14.5118	28.1920	32.0049	33.1795

AT TIME T = .55485 SECONDS, AFTER 299 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.0640	.1280	.1920	.2560	.3200	.3840	.4479	.5119	.5759	.6399	.7039	.7679	.8319	.8959
LOC.	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
U	.000	.045	.095	.158	.233	.312	.395	.483	.578	.680	.731	.765	.823	.912	1.017
Z	.025	.026	.027	.028	.029	.031	.033	.035	.036	.038	.042	.047	.051	.053	.056

DIST.	.9599	1.0239	1.0879
LOC.	15	16	17
U	1.099	1.129	1.233
Z	.059	.064	.073

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	1.3959	1.3954	1.3907	1.3930	1.3085	1.2942	1.2954	1.2960
H	11.3000	11.3219	11.3219	13.1104	26.1967	30.5246	32.1145	33.1790

AT TIME T = .57341 SECONDS, AFTER 309 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.0640	.1280	.1920	.2560	.3200	.3840	.4479	.5119	.5759	.6399	.7039	.7679	.8319	.8959
LOC.	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
U	.000	.039	.086	.144	.214	.289	.368	.452	.543	.636	.682	.714	.772	.859	.951
Z	.025	.026	.026	.027	.029	.030	.032	.034	.035	.037	.041	.045	.049	.052	.054

DIST.	.9599	1.0239	1.0879	1.1519
LOC.	15	16	17	18
U	1.035	1.070	1.145	1.394
Z	.057	.062	.064	.076

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	1.3948	1.3939	1.3892	1.3066	1.2849	1.2825	1.2865	1.2885
H	11.3000	11.3595	11.3595	25.8330	29.0624	30.1181	31.7431	33.1790

AT TIME T = .59197 SECONDS, AFTER 319 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.0640	.1280	.1920	.2560	.3200	.3840	.4479	.5119	.5759	.6399	.7039	.7679	.8319	.8959
LOC.	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
U	.000	.035	.077	.132	.198	.269	.343	.424	.511	.595	.636	.667	.725	.810	.899
Z	.025	.025	.026	.027	.028	.030	.031	.033	.034	.036	.040	.044	.047	.050	.052

DIST.	.9599	1.0239	1.0879	1.1519
LOC.	15	16	17	18
U	.977	1.014	1.090	1.215
Z	.055	.059	.062	.067

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	1.2292	1.2372	1.2330	1.2817	1.2806	1.2773	1.2756	1.2771
H	11.3000	13.6268	13.6268	28.4951	29.7469	30.2834	31.2286	33.1790

AT TIME T = .61052 SECONDS, AFTER 329 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.0640	.1280	.1920	.2560	.3200	.3840	.4479	.5119	.5759	.6399	.7039	.7679	.8319	.8959
LOC.	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
U	.000	.031	.070	.121	.182	.250	.321	.398	.480	.556	.593	.624	.682	.765	.850
Z	.025	.025	.026	.027	.028	.029	.031	.032	.034	.035	.039	.043	.046	.048	.050

DIST.	.9599	1.0239	1.0879	1.1519	1.2159
LOC.	15	16	17	18	19
U	.922	.961	1.036	1.127	1.179
Z	.053	.057	.060	.063	.075

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	1.1796	1.1799	1.1759	1.2074	1.2741	1.2738	1.2680	1.2628
H	11.3000	11.4860	11.4860	18.8599	29.7135	30.8549	31.7614	33.1790

AT TIME T = .62908 SECONDS, AFTER 339 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.0640	.1280	.1920	.2560	.3200	.3840	.4479	.5119	.5759	.6399	.7039	.7679	.8319	.8959
LOC.	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
U	.000	.028	.064	.111	.168	.233	.300	.374	.452	.520	.552	.583	.642	.722	.804
Z	.025	.025	.026	.026	.027	.029	.030	.031	.033	.035	.038	.042	.044	.047	.049

DIST.	.9599	1.0239	1.0879	1.1519	1.2159
LOC.	15	16	17	18	19
U	.871	.911	.985	1.057	1.089
Z	.052	.056	.058	.061	.067

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)

V	1.1704	1.1702	1.1663	1.1688	1.2010	1.2649	1.2611	1.2589
H	11.3000	11.3108	11.3108	14.0419	20.0131	31.1863	32.8408	33.1790

AT TIME T = .64764 SECONDS, AFTER 349 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.0640	.1280	.1920	.2560	.3200	.3840	.4479	.5119	.5759	.6399	.7039	.7679	.8319	.8959
LOC.	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
U	.000	.025	.058	.102	.156	.217	.282	.352	.425	.485	.514	.546	.605	.643	.760
Z	.025	.025	.025	.026	.027	.028	.029	.031	.032	.034	.037	.041	.043	.045	.048

DIST.	.9599	1.0239	1.0879	1.1519	1.2159	1.2799
LOC.	15	16	17	18	19	20
U	.823	.865	.937	.999	1.029	1.002
Z	.050	.054	.056	.059	.064	.074

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	1.1646	1.1644	1.1605	1.1600	1.1600	1.1886	1.2559	1.2594
H	11.3000	11.3082	11.3082	13.7555	15.5715	22.0399	32.6405	33.1790

AT TIME T = .66619 SECONDS, AFTER 359 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.0640	.1280	.1920	.2560	.3200	.3840	.4479	.5119	.5759	.6399	.7039	.7679	.8319	.8959
LOC.	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
U	.000	.023	.053	.094	.144	.202	.265	.331	.399	.452	.479	.511	.570	.645	.719
Z	.025	.025	.025	.026	.027	.028	.029	.030	.032	.034	.037	.040	.042	.044	.046

DIST.	.9599	1.0239	1.0879	1.1519	1.2159	1.2799
LOC.	15	16	17	18	19	20
U	.778	.821	.890	.946	.966	.950
Z	.049	.052	.055	.058	.062	.066

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	1.1581	1.1578	1.1539	1.1518	1.1479	1.1514	1.1873	1.2528
H	11.3000	11.3260	11.3260	14.1139	15.7920	17.0812	22.4666	33.1790

AT TIME T = .68475 SECONDS, AFTER 369 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.0640	.1280	.1920	.2560	.3200	.3840	.4479	.5119	.5759	.6399	.7039	.7679	.8319	.8959
LOC.	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
U	.000	.022	.049	.087	.134	.189	.249	.312	.374	.421	.446	.479	.538	.610	.680
Z	.025	.025	.025	.026	.026	.027	.028	.030	.031	.033	.036	.039	.041	.043	.045

DIST.	.9599	1.0239	1.0879	1.1519	1.2159	1.2799	1.3438
LOC.	15	16	17	18	19	20	21
U	.736	.780	.846	.896	.913	.917	1.060
Z	.048	.051	.053	.056	.061	.065	.068

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	1.1483	1.1477	1.1438	1.1418	1.1433	1.1466	1.1488	1.1158
H	11.3000	11.3983	11.3983	14.6361	15.6215	16.2337	17.7232	33.1790

AT TIME T = .70331 SECONDS, AFTER 379 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.0640	.1280	.1920	.2560	.3200	.3840	.4479	.5119	.5759	.6399	.7039	.7679	.8319	.8959
LOC.	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
U	.000	.020	.046	.081	.125	.176	.234	.294	.350	.392	.415	.449	.507	.577	.643
Z	.025	.025	.025	.025	.026	.027	.028	.029	.031	.033	.035	.038	.040	.042	.044

DIST.	.9599	1.0239	1.0879	1.1519	1.2159	1.2799	1.3438	1.4078
LOC.	15	16	17	18	19	20	21	22
U	.696	.741	.803	.848	.863	.885	.987	1.134
Z	.047	.050	.052	.055	.059	.063	.065	.077

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	1.1348	1.1343	1.1305	1.1354	1.1406	1.1407	1.0756	1.0456
H	11.3000	11.4250	11.4250	14.1822	15.0792	16.2673	26.9541	33.1790

AT TIME T = .72186 SECONDS, AFTER 389 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.0640	.1280	.1920	.2560	.3200	.3840	.4479	.5119	.5759	.6399	.7039	.7679	.8319	.8959
LOC.	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
U	.000	.019	.043	.075	.116	.165	.220	.276	.328	.364	.386	.422	.479	.546	.608
Z	.024	.025	.025	.025	.026	.027	.028	.029	.030	.032	.035	.037	.039	.041	.043

DIST.	.9599	1.0239	1.0879	1.1519	1.2159	1.2799	1.3438	1.4078
LOC.	15	16	17	18	19	20	21	22
U	.658	.704	.763	.802	.817	.849	.930	1.009
Z	.046	.048	.051	.054	.058	.061	.063	.067

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	1.1290	1.1285	1.1247	1.1294	1.1328	1.0699	1.0379	1.0355
H	11.3000	11.3318	11.3318	13.1504	14.8322	25.7526	31.7118	33.1790

AT TIME T = .74042 SECONDS, AFTER 399 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.0640	.1280	.1920	.2560	.3200	.3840	.4479	.5119	.5759	.6399	.7039	.7679	.8319	.8959
LOC.	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
U	.000	.040	.071	.109	.155	.207	.260	.306	.337	.359	.396	.452	.516	.575	.629
Z	.024	.024	.025	.025	.026	.026	.027	.028	.030	.032	.034	.037	.039	.040	.042

DIST.	.9599	1.0239	1.0879	1.1519	1.2159	1.2799	1.3438	1.4078	1.4718
LOC.	15	16	17	18	19	20	21	22	23

U	.623	.668	.723	.759	.774	.812	.886	.951	.966
Z	.045	.047	.050	.053	.057	.060	.061	.064	.074

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	1.1287	1.1282	1.1244	1.1253	1.0591	1.0305	1.0299	1.0333
H	11.3000	11.3259	11.3259	13.4314	23.7803	30.2245	32.0139	33.1790

AT TIME T = .75898 SECONDS, AFTER 409 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.0640	.1280	.1920	.2560	.3200	.3840	.4479	.5119	.5759	.6399	.7039	.7679	.8319	.8959
LOC.	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
U	.000	.017	.038	.066	.102	.145	.194	.244	.285	.312	.334	.371	.427	.488	.544
Z	.024	.024	.025	.025	.025	.026	.027	.028	.029	.031	.034	.036	.038	.039	.041

DIST.	.9599	1.0239	1.0879	1.1519	1.2159	1.2799	1.3438	1.4078	1.4718
LOC.	15	16	17	18	19	20	21	22	23
U	.589	.634	.686	.717	.734	.777	.846	.897	.912
Z	.044	.046	.048	.052	.055	.058	.060	.063	.065

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	1.1258	1.1253	1.1215	1.0564	1.0233	1.0192	1.0229	1.0244
H	11.3000	11.3302	11.3302	22.9968	28.7725	30.0390	31.7349	33.1790

AT TIME T = .77753 SECONDS, AFTER 419 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.0640	.1280	.1920	.2560	.3200	.3840	.4479	.5119	.5759	.6399	.7039	.7679	.8319	.8959
LOC.	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
U	.000	.016	.036	.063	.096	.136	.182	.228	.265	.288	.310	.349	.403	.461	.514
Z	.024	.024	.024	.025	.025	.026	.027	.028	.029	.031	.033	.035	.037	.039	.041

DIST.	.9599	1.0239	1.0879	1.1519	1.2159	1.2799	1.3438	1.4078	1.4718	1.5358
LOC.	15	16	17	18	19	20	21	22	23	24
U	.558	.602	.649	.677	.697	.743	.808	.854	.874	.900
Z	.043	.045	.048	.051	.054	.057	.058	.061	.064	.068

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	1.0110	1.0118	1.0084	1.0200	1.0166	1.0158	1.0137	1.0155
H	11.3000	14.2594	14.2594	27.8842	29.2493	30.2844	31.2491	33.1790

AT TIME T = .79609 SECONDS, AFTER 429 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.0640	.1280	.1920	.2560	.3200	.3840	.4479	.5119	.5759	.6399	.7039	.7679	.8319	.8959
LOC.	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
U	.000	.016	.035	.059	.090	.128	.171	.213	.245	.266	.288	.327	.380	.436	.485
Z	.024	.024	.024	.025	.025	.026	.026	.027	.029	.031	.033	.035	.036	.038	.040

DIST.	.9599	1.0239	1.0879	1.1519	1.2159	1.2799	1.3438	1.4078	1.4718	1.5358
LOC.	15	16	17	18	19	20	21	22	23	24
U	.528	.571	.614	.640	.662	.710	.771	.812	.835	.862
Z	.042	.044	.047	.050	.053	.055	.057	.060	.063	.065

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	.9232	.9239	.9208	.9688	1.0125	1.0111	1.0084	1.0031
H	11.3000	11.5783	11.5783	21.8117	29.3944	30.4585	31.7708	33.1790

AT TIME T = .81465 SECONDS, AFTER 439 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.0640	.1280	.1920	.2560	.3200	.3840	.4479	.5119	.5759	.6399	.7039	.7679	.8319	.8959
LOC.	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
U	.000	.015	.033	.056	.085	.121	.160	.197	.226	.246	.268	.307	.359	.411	.458
Z	.024	.024	.024	.024	.025	.025	.026	.027	.029	.031	.033	.034	.036	.037	.039

DIST.	.9599	1.0239	1.0879	1.1519	1.2159	1.2799	1.3438	1.4078	1.4718	1.5358	1.5998
LOC.	15	16	17	18	19	20	21	22	23	24	25
U	.499	.541	.580	.604	.629	.678	.735	.773	.798	.823	.857
Z	.041	.044	.046	.049	.052	.054	.056	.059	.062	.065	.069

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	.9126	.9125	.9094	.9136	.9635	1.0052	1.0006	1.0014
H	11.3000	11.3163	11.3163	14.4106	23.0477	30.8779	32.4266	33.1790

AT TIME T = .83321 SECONDS, AFTER 449 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.0640	.1280	.1920	.2560	.3200	.3840	.4479	.5119	.5759	.6399	.7039	.7679	.8319	.8959
LOC.	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
U	.000	.015	.032	.054	.081	.113	.149	.183	.208	.226	.250	.288	.338	.388	.432
Z	.024	.024	.024	.024	.025	.025	.026	.027	.028	.030	.032	.034	.035	.037	.039

DIST.	.9599	1.0239	1.0879	1.1519	1.2159	1.2799	1.3438	1.4078	1.4718	1.5358	1.5998
LOC.	15	16	17	18	19	20	21	22	23	24	25
U	.472	.511	.547	.570	.598	.647	.700	.735	.761	.785	.809
Z	.041	.043	.045	.048	.051	.053	.055	.058	.061	.064	.066

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	.9079	.9078	.9047	.9043	.9067	.9532	.9982	.9980
H	11.3000	11.3128	11.3128	13.8469	15.9368	25.0393	32.3248	33.1790

AT TIME T = .85176 SECONDS, AFTER 459 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.0640	.1280	.1920	.2560	.3200	.3840	.4479	.5119	.5759	.6399	.7039	.7679	.8319	.8959
LOC.	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14

U	.000	.014	.031	.051	.077	.107	.139	.168	.190	.208	.232	.271	.318	.356	.[illegible]7
Z	.024	.024	.024	.024	.025	.025	.026	.027	.028	.030	.032	.033	.035	.036	.038

DIST.	.9599	1.0239	1.0879	1.1519	1.2159	1.2799	1.3438	1.4078	1.4718	1.5358	1.5998	1.6638
LOC.	15	16	17	18	19	20	21	22	23	24	25	26
U	.446	.483	.516	.538	.569	.617	.667	.700	.725	.751	.781	.902
Z	.040	.042	.045	.047	.050	.052	.054	.057	.060	.062	.064	.075

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	.9026	.9024	.8994	.8978	.8942	.9000	.9509	.9961
H	11.3000	11.3304	11.3304	14.1162	15.8527	17.4250	25.8606	33.1790

AT TIME T = .87032 SECONDS, AFTER 469 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.0640	.1280	.1920	.2560	.3200	.3840	.4479	.5119	.5759	.6399	.7039	.7679	.8319	.8959
LOC.	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
U	.000	.014	.030	.049	.073	.100	.129	.154	.173	.190	.216	.254	.299	.344	.384
Z	.024	.024	.024	.024	.024	.025	.026	.027	.028	.030	.031	.033	.034	.036	.038

DIST.	.9599	1.0239	1.0879	1.1519	1.2159	1.2799	1.3438	1.4078	1.4718	1.5358	1.5998	1.6638
LOC.	15	16	17	18	19	20	21	22	23	24	25	26
U	.420	.456	.486	.508	.541	.588	.634	.665	.690	.718	.745	.802
Z	.040	.042	.044	.047	.049	.051	.053	.056	.059	.061	.064	.068

FULL-FLOWING PIPE SYSTEN

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	.8947	.8944	.8914	.8893	.8912	.8920	.8971	.9042
H	11.3000	11.3866	11.3866	14.6112	15.6034	16.6907	18.3661	33.1790

AT TIME T = .88888 SECONDS, AFTER 479 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.0640	.1280	.1920	.2560	.3200	.3840	.4479	.5119	.5759	.6399	.7039	.7679	.8319	.8959
LOC.	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
U	.000	.014	.029	.047	.069	.094	.119	.140	.157	.174	.200	.238	.282	.324	.361
Z	.024	.024	.024	.024	.024	.025	.025	.026	.028	.030	.031	.033	.034	.035	.037

DIST.	.9599	1.0239	1.0879	1.1519	1.2159	1.2799	1.3438	1.4078	1.4718	1.5358	1.5998	1.6638	1.7278
LOC.	15	16	17	18	19	20	21	22	23	24	25	26	27
U	.396	.429	.457	.480	.514	.560	.603	.632	.657	.685	.715	.759	.882
Z	.039	.041	.043	.046	.048	.050	.052	.055	.058	.060	.063	.065	.077

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	.8830	.8828	.8798	.8849	.8871	.8883	.8456	.7999
H	11.3000	11.4223	11.4223	14.1505	15.4495	16.5468	24.0387	33.1790

AT TIME T = .90743 SECONDS, AFTER 489 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.0640	.1280	.1920	.2560	.3200	.3840	.4479	.5119	.5759	.6399	.7039	.7679	.8319	.8959
LOC.	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
U	.000	.014	.028	.045	.065	.087	.109	.127	.141	.158	.185	.223	.264	.314	.359
Z	.024	.024	.024	.024	.024	.025	.025	.026	.028	.029	.031	.032	.033	.035	.037

DIST.	.9599	1.0239	1.0879	1.1519	1.2159	1.2799	1.3438	1.4078	1.4718	1.5358	1.5998	1.6638	1.7278
LOC.	15	16	17	18	19	20	21	22	23	24	25	26	27
U	.373	.404	.429	.453	.488	.533	.572	.600	.625	.653	.685	.720	.785
Z	.038	.041	.043	.045	.047	.049	.051	.054	.057	.059	.062	.064	.068

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	.8797	.8793	.8763	.8777	.8820	.8409	.7913	.7872
H	11.3000	11.3236	11.3236	13.5408	15.0965	22.7689	31.3638	33.1790

AT TIME T = .92599 SECONDS, AFTER 499 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.0640	.1280	.1920	.2560	.3200	.3840	.4479	.5119	.5759	.6399	.7039	.7679	.8319	.8959
LOC.	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
U	.000	.013	.028	.044	.062	.081	.100	.114	.127	.144	.171	.208	.248	.285	.319
Z	.024	.024	.024	.024	.024	.025	.025	.026	.028	.029	.031	.032	.033	.035	.036

DIST.	.9599	1.0239	1.0879	1.1519	1.2159	1.2799	1.3438	1.4078	1.4718	1.5358	1.5998	1.6638	1.7278	1.7918
LOC.	15	16	17	18	19	20	21	22	23	24	25	26	27	28
U	.350	.379	.403	.428	.463	.506	.543	.569	.594	.623	.655	.689	.740	.878
Z	.038	.040	.042	.045	.047	.049	.051	.053	.056	.058	.061	.063	.065	.077

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	.8786	.8780	.8750	.8749	.8818	.7853	.7626	.7828
H	11.3000	11.3375	11.3375	13.5147	20.8342	29.8760	31.9428	33.1790

AT TIME T = .94455 SECONDS, AFTER 509 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.0640	.1280	.1920	.2560	.3200	.3840	.4479	.5119	.5759	.6399	.7039	.7679	.8319	.8959
LOC.	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
U	.000	.013	.027	.042	.058	.075	.090	.102	.113	.130	.158	.194	.232	.267	.298
Z	.024	.024	.024	.024	.024	.024	.025	.026	.028	.029	.030	.031	.033	.034	.036

DIST.	.9599	1.0239	1.0879	1.1519	1.2159	1.2799	1.3438	1.4078	1.4718	1.5358	1.5998	1.6638	1.7278	1.7918
LOC.	15	16	17	18	19	20	21	22	23	24	25	26	27	28
U	.328	.355	.378	.403	.439	.480	.514	.539	.564	.593	.626	.661	.698	.766
Z	.038	.040	.042	.044	.046	.048	.050	.052	.055	.057	.060	.062	.064	.068

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	.8756	.8753	.8723	.8293	.7785	.7735	.7768	.7786
H	11.3000	11.3239	11.3239	19.8778	28.2585	30.0019	31.7341	33.1790

AT TIME T = .96310 SECONDS, AFTER 519 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.0640	.1280	.1920	.2560	.3200	.3840	.4479	.5119	.5759	.6399	.7039	.7679	.8319	.8959
LOC.	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
U	.000	.013	.026	.040	.055	.069	.081	.090	.100	.117	.145	.180	.217	.250	.279
Z	.024	.024	.024	.024	.024	.024	.025	.026	.027	.029	.030	.031	.032	.034	.035

DIST.	.9599	1.0239	1.0879	1.1519	1.2159	1.2799	1.3438	1.4078	1.4718	1.5358	1.5998	1.6638	1.7278	1.7918	1.8558
LOC.	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29
U	.307	.331	.354	.380	.416	.455	.486	.511	.536	.565	.598	.633	.669	.720	.801
Z	.037	.039	.041	.043	.045	.047	.049	.052	.054	.056	.059	.061	.063	.065	.078

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	.8070	.8031	.8004	.7762	.7711	.7700	.7690	.7709
H	11.3000	13.7547	13.7547	27.3066	29.0369	30.1183	31.2820	33.1790

AT TIME T = .98166 SECONDS, AFTER 529 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.0640	.1280	.1920	.2560	.3200	.3840	.4479	.5119	.5759	.6399	.7039	.7679	.8319	.8959
LOC.	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
U	.000	.013	.025	.038	.051	.063	.072	.079	.088	.105	.133	.167	.201	.233	.260
Z	.024	.024	.024	.024	.024	.024	.025	.026	.027	.029	.030	.031	.032	.034	.035

DIST.	.9599	1.0239	1.0879	1.1519	1.2159	1.2799	1.3438	1.4078	1.4718	1.5358	1.5998	1.6638	1.7278	1.7918	1.8558
LOC.	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29
U	.286	.309	.331	.358	.394	.430	.459	.483	.508	.538	.571	.606	.641	.674	.718
Z	.037	.039	.041	.043	.045	.047	.049	.051	.053	.056	.058	.060	.062	.064	.072

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	.6839	.6861	.6838	.7424	.7677	.7666	.7641	.7609
H	11.3000	11.8018	11.8018	24.1979	29.1653	30.3164	31.6060	33.1790

AT TIME T = 1.00022 SECONDS, AFTER 539 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.0640	.1280	.1920	.2560	.3200	.3840	.4479	.5119	.5759	.6399	.7039	.7679	.8319	.8959
LOC.	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
U	.000	.012	.025	.037	.048	.057	.064	.069	.077	.094	.121	.154	.187	.216	.242
Z	.023	.023	.024	.024	.024	.024	.025	.026	.027	.028	.029	.031	.032	.033	.035

DIST.	.9599	1.0239	1.0879	1.1519	1.2159	1.2799	1.3438	1.4078	1.4718	1.5358	1.5998	1.6638	1.7278	1.7918	1.8558
LOC.	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29
U	.266	.287	.310	.337	.372	.406	.433	.457	.482	.512	.545	.579	.612	.635	.663
Z	.037	.038	.040	.042	.044	.046	.048	.050	.053	.055	.057	.059	.061	.064	.068

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	.6704	.6706	.6683	.6755	.7380	.7618	.7577	.7574
H	11.3000	11.3493	11.3493	14.9698	25.4916	30.6508	32.2528	33.1790

AT TIME T = 1.01877 SECONDS, AFTER 549 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.0640	.1280	.1920	.2560	.3200	.3840	.4479	.5119	.5759	.6399	.7039	.7679	.8319	.8959
LOC.	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
U	.000	.012	.024	.035	.044	.051	.055	.059	.066	.083	.110	.141	.172	.200	.225
Z	.023	.023	.023	.024	.024	.024	.025	.026	.027	.028	.029	.030	.032	.033	.035

DIST.	.9599	1.0239	1.0879	1.1519	1.2159	1.2799	1.3438	1.4078	1.4718	1.5358	1.5998	1.6638	1.7278	1.7918	1.8558
LOC.	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29
U	.247	.267	.289	.317	.350	.382	.408	.431	.457	.487	.520	.553	.583	.611	.627
Z	.036	.038	.040	.042	.044	.045	.048	.050	.052	.054	.056	.058	.060	.063	.065

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	.6664	.6663	.6640	.6646	.6699	.7292	.7551	.7553
H	11.3000	11.3205	11.3205	13.9370	16.4854	27.4400	32.2629	33.1790

AT TIME T = 1.03733 SECONDS, AFTER 559 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.1280	.2560	.3840	.5119	.6399	.7679	.8959	1.0239	1.1519	1.2799	1.4078	1.5358	1.6638	1.7918
LOC.	0	2	4	6	8	10	12	14	16	18	20	22	24	26	28
U	.000	.023	.040	.047	.057	.099	.158	.207	.247	.297	.359	.407	.463	.527	.573
Z	.023	.023	.024	.025	.027	.029	.031	.034	.038	.041	.045	.049	.053	.057	.062

DIST.	1.9198
LOC.	30
U	.605
Z	.071

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	.6620	.6619	.6597	.6584	.6554	.6634	.7270	.7528
H	11.3000	11.3340	11.3340	14.1129	15.8997	18.1262	28.4228	33.1790

AT TIME T = 1.05589 SECONDS, AFTER 569 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.1280	.2560	.3840	.5119	.6399	.7679	.8959	1.0239	1.1519	1.2799	1.4078	1.5358	1.6638	1.7918
LOC.	0	2	4	6	8	10	12	14	16	18	20	22	24	26	28
U	.000	.021	.036	.039	.048	.089	.144	.190	.229	.278	.337	.383	.440	.502	.541
Z	.023	.023	.024	.025	.027	.029	.031	.034	.038	.041	.045	.049	.053	.057	.061

DIST.	1.9198
LOC.	30
U	.560
Z	.068

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)

V	.6555	.6554	.6532	.6510	.6520	.6533	.6614	.6989
H	11.3000	11.3805	11.3805	14.5726	15.7521	16.8989	19.1162	3 .1749

AT TIME T = 1.07445 SECONDS, AFTER 579 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.1280	.2560	.3840	.5119	.6399	.7679	.8959	1.0239	1.1519	1.2799	1.4078	1.5358	1.6638	1.7918
LOC.	0	2	4	6	8	10	12	14	16	18	20	22	24	26	28
U	.000	.020	.032	.032	.039	.079	.130	.174	.211	.260	.315	.361	.417	.477	.539
Z	.023	.023	.024	.025	.027	.029	.031	.034	.037	.041	.044	.048	.052	.056	.061

DIST.	1.9198
LOC.	30
U	.538
Z	.065

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	.6453	.6454	.6431	.6468	.6489	.6499	.6253	.5753
H	11.3000	11.4289	11.4289	14.2962	15.5721	16.7433	21.6973	33.1790

AT TIME T = 1.09300 SECONDS, AFTER 589 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.1280	.2560	.3840	.5119	.6399	.7679	.8959	1.0239	1.1519	1.2799	1.4078	1.5358	1.6638	1.7918
LOC.	0	2	4	6	8	10	12	14	16	18	20	22	24	26	28
U	.000	.019	.028	.024	.032	.069	.117	.157	.194	.242	.294	.339	.395	.451	.508
Z	.023	.023	.024	.025	.027	.029	.031	.034	.037	.040	.044	.048	.051	.055	.060

DIST.	1.9198	1.9838
LOC.	30	31
U	.513	.585
Z	.065	.069

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	.6430	.6423	.6402	.6410	.6448	.6212	.5590	.5525
H	11.3000	11.3465	11.3465	13.7081	15.2893	20.3551	30.8202	33.1790

AT TIME T = 1.11156 SECONDS, AFTER 599 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.1280	.2560	.3840	.5119	.6399	.7679	.8959	1.0239	1.1519	1.2799	1.4078	1.5358	1.6638	1.7918
LOC.	0	2	4	6	8	10	12	14	16	18	20	22	24	26	28
U	.000	.017	.024	.018	.024	.060	.104	.141	.177	.225	.274	.318	.374	.426	.483
Z	.023	.023	.024	.025	.027	.028	.031	.033	.037	.040	.043	.047	.051	.055	.060

DIST.	1.9198	1.9838
LOC.	30	31
U	.490	.535
Z	.064	.066

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	.6408	.6404	.6383	.6382	.6133	.5541	.5479	.5478
H	11.3000	11.3257	11.3257	13.6195	18.4772	29.3393	31.8684	33.1790

AT TIME T = 1.13012 SECONDS, AFTER 609 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.1280	.2560	.3840	.5119	.6399	.7679	.8959	1.0239	1.1519	1.2799	1.4078	1.5358	1.6638	1.7918
LOC.	0	2	4	6	8	10	12	14	16	18	20	22	24	26	28
U	.000	.016	.019	.011	.017	.051	.091	.126	.161	.208	.254	.298	.353	.412	.427
Z	.023	.023	.024	.025	.027	.028	.030	.033	.036	.040	.043	.047	.050	.054	.059

DIST.	1.9198	1.9838	2.0478
LOC.	30	31	32
U	.471	.510	.638
Z	.063	.065	.076

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	.6384	.6381	.6360	.6107	.5477	.5402	.5428	.5438
H	11.3000	11.3204	11.3204	17.3568	27.6433	29.9815	31.7420	33.1790

AT TIME T = 1.14867 SECONDS, AFTER 619 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.1280	.2560	.3840	.5119	.6399	.7679	.8959	1.0239	1.1519	1.2799	1.4078	1.5358	1.6638	1.7918
LOC.	0	2	4	6	8	10	12	14	16	18	20	22	24	26	28
U	.000	.014	.014	.005	.011	.042	.078	.110	.145	.192	.235	.279	.332	.377	.402
Z	.023	.023	.024	.025	.027	.028	.030	.033	.036	.039	.043	.046	.050	.054	.059

DIST.	1.9198	1.9838	2.0478
LOC.	30	31	32
U	.451	.477	.543
Z	.063	.064	.069

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	.6007	.5963	.5943	.5457	.5376	.5365	.5361	.5379
H	11.3000	12.9274	12.9274	26.5941	28.8506	30.0483	31.3356	33.1790

AT TIME T = 1.16723 SECONDS, AFTER 629 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.1280	.2560	.3840	.5119	.6399	.7679	.8959	1.0239	1.1519	1.2799	1.4078	1.5358	1.6638	1.7918
LOC.	0	2	4	6	8	10	12	14	16	18	20	22	24	26	28
→ U	.000	.011	.010	-.001	.005	.033	.066	.095	.130	.175	.217	.260	.312	.353	.379 ←
Z	.023	.023	.024	.025	.027	.028	.030	.033	.036	.039	.042	.046	.049	.053	.058

DIST.	1.9198	1.9838	2.0478
LOC.	30	31	32

U	.429	.453	.499
Z	.062	.064	.067

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	.4605	.4642	.4626	.5213	.5345	.5336	.5316	.5284
H	11.3000	12.3306	12.3306	25.6961	28.9998	30.2044	31.5278	33.1797

AT TIME T = 1.18579 SECONDS, AFTER 639 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.1280	.2560	.3840	.5119	.6399	.7679	.8959	1.0239	1.1519	1.2799	1.4078	1.5358	1.6638	1.7918
LOC.	0	2	4	6	8	10	12	14	16	18	20	22	24	26	28
U	.000	.009	.005	-.007	-.001	.025	.054	.081	.115	.159	.199	.242	.292	.339	.388
Z	.023	.023	.024	.025	.026	.028	.030	.033	.036	.039	.042	.046	.049	.053	.057

DIST.	1.9198	1.9838	2.0478
LOC.	30	31	32
U	.408	.431	.467
Z	.061	.063	.066

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	.4394	.4396	.4382	.4516	.5173	.5296	.5259	.5252
H	11.3000	11.3992	11.3992	16.0394	27.0570	30.4780	32.0881	33.1790

AT TIME T = 1.20434 SECONDS, AFTER 649 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.1280	.2560	.3840	.5119	.6399	.7679	.8959	1.0239	1.1519	1.2799	1.4078	1.5358	1.6638	1.7918
LOC.	0	2	4	6	8	10	12	14	16	18	20	22	24	26	28
U	.000	.007	.000	-.013	-.007	.017	.042	.067	.101	.143	.182	.224	.272	.316	.337
Z	.023	.023	.024	.025	.026	.028	.030	.033	.036	.039	.042	.045	.049	.053	.057

DIST.	1.9198	1.9838	2.0478
LOC.	30	31	32
U	.386	.409	.441
Z	.061	.062	.065

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	.4352	.4352	.4337	.4343	.4469	.5097	.5233	.5234
H	11.3000	11.3296	11.3296	14.0531	17.5409	28.9463	32.1696	33.1790

AT TIME T = 1.22290 SECONDS, AFTER 659 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.1280	.2560	.3840	.5119	.6399	.7679	.8959	1.0239	1.1519	1.2799	1.4078	1.5358	1.6638	1.7918
LOC.	0	2	4	6	8	10	12	14	16	18	20	22	24	26	28
U	.000	.004	-.005	-.018	-.013	.008	.031	.054	.087	.127	.165	.207	.252	.284	.316
Z	.023	.023	.024	.025	.026	.028	.030	.033	.035	.038	.042	.045	.048	.052	.056

DIST.	1.9198	1.9838	2.0478	2.1118
LOC.	30	31	32	33
U	.365	.388	.397	.395
Z	.060	.062	.065	.070

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	.4315	.4314	.4300	.4293	.4268	.4407	.5073	.5213
H	11.3000	11.3400	11.3400	14.1068	15.9561	19.2552	30.0867	33.1795

AT TIME T = 1.24146 SECONDS, AFTER 669 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.1280	.2560	.3840	.5119	.6399	.7679	.8959	1.0239	1.1519	1.2799	1.4078	1.5358	1.6638	1.7918
LOC.	0	2	4	6	8	10	12	14	16	18	20	22	24	26	28
U	.000	.001	-.009	-.023	-.018	.000	.020	.041	.073	.112	.149	.191	.233	.262	.297
Z	.023	.023	.024	.025	.026	.028	.030	.032	.035	.038	.041	.044	.048	.052	.056

DIST.	1.9198	1.9838	2.0478	2.1118
LOC.	30	31	32	33
U	.345	.362	.356	.358
Z	.059	.061	.065	.068

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	.4261	.4261	.4246	.4225	.4228	.4245	.4389	.4913
H	11.3000	11.3779	11.3779	14.5192	15.8187	17.1117	20.3308	33.1790

AT TIME T = 1.26001 SECONDS, AFTER 679 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.1280	.2560	.3840	.5119	.6399	.7679	.8959	1.0239	1.1519	1.2799	1.4078	1.5358	1.6638	1.7918
LOC.	0	2	4	6	8	10	12	14	16	18	20	22	24	26	28
U	.000	-.001	-.014	-.027	-.024	-.008	.009	.029	.060	.097	.133	.175	.214	.241	.278
Z	.023	.023	.024	.025	.026	.028	.030	.032	.035	.038	.041	.044	.048	.052	.055

DIST.	1.9198	1.9838	2.0478	2.1118
LOC.	30	31	32	33
U	.323	.333	.327	.338
Z	.059	.061	.064	.066

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	.4172	.4172	.4158	.4185	.4202	.4210	.4086	.3569
H	11.3000	11.4333	11.4333	14.3670	15.6751	16.8935	20.2529	33.1790

AT TIME T = 1.27857 SECONDS, AFTER 689 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.1280	.2560	.3840	.5119	.6399	.7679	.8959	1.0239	1.1519	1.2799	1.4078	1.5358	1.6638	1.7918
LOC.	0	2	4	6	8	10	12	14	16	18	20	22	24	26	28

U	.000	-.004	-.019	-.032	-.029	-.016	-.002	.017	.047	.082	.118	.158	.195	.232	.269
Z	.023	.023	.024	.025	.026	.028	.030	.032	.035	.038	.041	.044	.047	.051	.054

DIST.	1.9198	1.9838	2.0478	2.1118
LOC.	30	31	32	33
U	.299	.305	.306	.324
Z	.059	.061	.064	.065

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	.4138	.4134	.4120	.4134	.4167	.4044	.3391	.3261
H	11.3000	11.3260	11.3260	13.8683	15.4428	18.8085	29.7597	33.1790

AT TIME T = 1.29713 SECONDS, AFTER 699 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.1280	.2560	.3840	.5119	.6399	.7679	.8959	1.0239	1.1519	1.2799	1.4078	1.5358	1.6638	1.7918
LOC.	0	2	4	6	8	10	12	14	16	18	20	22	24	26	28
U	.000	-.007	-.023	-.036	-.034	-.024	-.013	.005	.034	.067	.102	.142	.176	.206	.241
Z	.023	.023	.024	.025	.026	.028	.030	.032	.035	.038	.041	.044	.047	.051	.054

DIST.	1.9198	1.9838	2.0478	2.1118	2.1757
LOC.	30	31	32	33	34
U	.275	.280	.290	.300	.362
Z	.058	.061	.063	.065	.072

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	.4120	.4117	.4103	.4103	.3977	.3349	.3220	.3214
H	11.3000	11.3203	11.3203	13.6808	16.0951	28.2870	31.7649	33.1790

AT TIME T = 1.31569 SECONDS, AFTER 709 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.1280	.2560	.3840	.5119	.6399	.7679	.8959	1.0239	1.1519	1.2799	1.4078	1.5358	1.6638	1.7918
LOC.	0	2	4	6	8	10	12	14	16	18	20	22	24	26	28
U	.000	-.011	-.028	-.040	-.039	-.032	-.023	-.006	.022	.053	.088	.126	.158	.185	.223
Z	.023	.023	.024	.025	.026	.028	.030	.032	.035	.037	.040	.043	.047	.051	.054

DIST.	1.9198	1.9838	2.0478	2.1118	2.1757
LOC.	30	31	32	33	34
U	.252	.257	.268	.274	.312
Z	.058	.060	.063	.065	.068

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	.4100	.4098	.4084	.3947	.3287	.3154	.3172	.3179
H	11.3000	11.3211	11.3211	15.7171	26.5036	29.9410	31.7518	33.1790

AT TIME T = 1.33424 SECONDS, AFTER 719 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.1280	.2560	.3840	.5119	.6399	.7679	.8959	1.0239	1.1519	1.2799	1.4078	1.5358	1.6638	1.7918
LOC.	0	2	4	6	8	10	12	14	16	18	20	22	24	26	28
U	.000	-.014	-.032	-.044	-.044	-.040	-.033	-.017	.009	.040	.073	.110	.140	.167	.204
Z	.023	.023	.024	.025	.026	.028	.030	.032	.035	.037	.040	.043	.047	.050	.054

DIST.	1.9198	1.9838	2.0478	2.1118	2.1757
LOC.	30	31	32	33	34
U	.229	.235	.246	.258	.290
Z	.058	.060	.062	.064	.065

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	.3900	.3868	.3855	.3270	.3125	.3109	.3113	.3130
H	11.3000	12.2530	12.2530	25.3990	28.6512	29.9721	31.3982	33.1790

AT TIME T = 1.35280 SECONDS, AFTER 729 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.1280	.2560	.3840	.5119	.6399	.7679	.8959	1.0239	1.1519	1.2799	1.4078	1.5358	1.6638	1.7918
LOC.	0	2	4	6	8	10	12	14	16	18	20	22	24	26	28
U	.000	-.017	-.036	-.048	-.050	-.047	-.043	-.028	-.003	.026	.059	.094	.122	.150	.185
Z	.023	.024	.024	.025	.026	.028	.030	.032	.034	.037	.040	.043	.046	.050	.053

DIST.	1.9198	1.9838	2.0478	2.1118	2.1757	2.2397
LOC.	30	31	32	33	34	35
U	.207	.214	.226	.246	.252	.279
Z	.058	.060	.062	.064	.066	.070

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	.2547	.2580	.2571	.3034	.3092	.3084	.3067	.3048
H	11.3000	12.9740	12.9740	26.4569	28.8703	30.1084	31.4416	33.1790

AT TIME T = 1.37136 SECONDS, AFTER 739 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.1280	.2560	.3840	.5119	.6399	.7679	.8959	1.0239	1.1519	1.2799	1.4078	1.5358	1.6638	1.7918
LOC.	0	2	4	6	8	10	12	14	16	18	20	22	24	26	28
U	.000	-.020	-.040	-.052	-.055	-.055	-.052	-.038	-.014	.013	.045	.078	.105	.133	.166
Z	.023	.024	.024	.025	.026	.028	.030	.032	.034	.037	.040	.043	.046	.050	.053

DIST.	1.9198	1.9838	2.0478	2.1118	2.1757	2.2397
LOC.	30	31	32	33	34	35
U	.185	.194	.208	.224	.229	.216
Z	.057	.060	.061	.063	.066	.075

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	.2165	.2169	.2161	.2395	.2993	.3051	.3018	.3005
H	11.3000	11.4523	11.4523	17.7517	27.9177	30.3390	31.9299	33.1790

AT TIME T = 1.38991 SECONDS, AFTER 749 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.1280	.2560	.3840	.5119	.6399	.7679	.8959	1.0239	1.1519	1.2799	1.4078	1.5358	1.6638	1.7918
LOC.	0	2	4	6	8	10	12	14	16	18	20	22	24	26	28
U	.000	-.023	-.044	-.056	-.060	-.063	-.061	-.048	-.026	.001	.032	.063	.088	.117	.147
Z	.023	.024	.024	.025	.026	.028	.030	.032	.034	.037	.040	.043	.046	.049	.053

DIST.	1.9198	1.9838	2.0478	2.1118	2.1757	2.2397
LOC.	30	31	32	33	34	35
U	.165	.175	.189	.200	.189	.187
Z	.057	.059	.061	.063	.066	.072

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	.2116	.2116	.2109	.2123	.2355	.2928	.2988	.2989
H	11.3000	11.3398	11.3398	14.2229	19.2499	29.7417	32.1175	33.1790

AT TIME T = 1.40847 SECONDS, AFTER 759 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.1280	.2560	.3840	.5119	.6399	.7679	.8959	1.0239	1.1519	1.2799	1.4078	1.5358	1.6638	1.7918
LOC.	0	2	4	6	8	10	12	14	16	18	20	22	24	26	28
U	.000	-.026	-.048	-.060	-.065	-.070	-.070	-.058	-.037	-.012	.018	.047	.071	.100	.128
Z	.023	.024	.025	.025	.026	.028	.030	.032	.034	.037	.039	.042	.046	.049	.053

DIST.	1.9198	1.9838	2.0478	2.1118	2.1757	2.2397
LOC.	30	31	32	33	34	35
U	.145	.156	.169	.171	.161	.168
Z	.057	.059	.061	.063	.066	.069

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	.2085	.2085	.2078	.2070	.2060	.2295	.2899	.2971
H	11.3000	11.3470	11.3470	14.1206	16.0774	21.0602	31.0366	33.1790

AT TIME T = 1.42703 SECONDS, AFTER 769 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.1280	.2560	.3840	.5119	.6399	.7679	.8959	1.0239	1.1519	1.2799	1.4078	1.5358	1.6638	1.7918
LOC.	0	2	4	6	8	10	12	14	16	18	20	22	24	26	28
U	.000	-.029	-.051	-.064	-.071	-.077	-.079	-.068	-.048	-.024	.005	.032	.055	.084	.109
Z	.023	.024	.025	.025	.026	.028	.030	.032	.034	.037	.039	.042	.046	.049	.053

DIST.	1.9198	1.9838	2.0478	2.1118	2.1757	2.2397
LOC.	30	31	32	33	34	35
U	.126	.137	.146	.144	.141	.155
Z	.057	.059	.061	.063	.066	.067

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	.2041	.2040	.2034	.2015	.2010	.2033	.2281	.2809
H	11.3000	11.3776	11.3776	14.4783	15.9325	17.4039	22.1983	33.1790

AT TIME T = 1.44558 SECONDS, AFTER 779 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.1280	.2560	.3840	.5119	.6399	.7679	.8959	1.0239	1.1519	1.2799	1.4078	1.5358	1.6638	1.7918
LOC.	0	2	4	6	8	10	12	14	16	18	20	22	24	26	28
U	.000	-.031	-.055	-.067	-.076	-.085	-.087	-.077	-.059	-.036	-.008	.017	.040	.068	.090
Z	.024	.024	.025	.025	.026	.028	.030	.032	.034	.037	.039	.042	.045	.049	.052

DIST.	1.9198	1.9838	2.0478	2.1118	2.1757	2.2397
LOC.	30	31	32	33	34	35
U	.107	.117	.122	.120	.126	.146
Z	.056	.058	.061	.063	.065	.066

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	.1965	.1965	.1958	.1974	.1988	.1996	.1946	.1595
H	11.3000	11.4337	11.4337	14.4673	15.8046	17.0710	19.6157	33.1790

AT TIME T = 1.46414 SECONDS, AFTER 789 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.1280	.2560	.3840	.5119	.6399	.7679	.8959	1.0239	1.1519	1.2799	1.4078	1.5358	1.6638	1.7918
LOC.	0	2	4	6	8	10	12	14	16	18	20	22	24	26	28
U	.000	-.034	-.058	-.071	-.082	-.092	-.095	-.087	-.070	-.047	-.021	.002	.025	.051	.071
Z	.024	.024	.025	.025	.027	.028	.030	.032	.034	.036	.039	.042	.045	.049	.052

DIST.	1.9198	1.9838	2.0478	2.1118	2.1757	2.2397
LOC.	30	31	32	33	34	35
U	.088	.096	.098	.100	.115	.138
Z	.056	.058	.061	.063	.065	.065

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	.1918	.1916	.1909	.1931	.1959	.1901	.1309	.1083
H	11.3000	11.3168	11.3168	14.0380	15.6060	18.0134	28.0898	33.1790

AT TIME T = 1.48270 SECONDS, AFTER 799 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.1280	.2560	.3840	.5119	.6399	.7679	.8959	1.0239	1.1519	1.2799	1.4078	1.5358	1.6638	1.7918
LOC.	0	2	4	6	8	10	12	14	16	18	20	22	24	26	28
U	.000	-.036	-.061	-.075	-.087	-.099	-.103	-.096	-.080	-.059	-.035	-.013	.010	.035	.053
Z	.024	.024	.025	.026	.027	.028	.030	.032	.034	.036	.039	.042	.045	.048	.052

DIST.	1.9198	1.9838	2.0478	2.1118	2.1757	2.2397	2.3037
LOC.	30	31	32	33	34	35	36
U	.068	.074	.077	.083	.106	.131	.190
Z	.056	.058	.060	.063	.064	.064	.078

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)

V	.1904	.1903	.1896	.1895	.1844	.1273	.1037	.1022
H	11.3000	11.3220	11.3220	13.7328	16.2447	26.6277	31.6333	33.1790

AT TIME T = 1.50125 SECONDS, AFTER 809 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.1280	.2560	.3840	.5119	.6399	.7679	.8959	1.0239	1.1519	1.2799	1.4078	1.5358	1.6638	1.7918
LOC.	0	2	4	6	8	10	12	14	16	18	20	22	24	26	28
U	.000	-.038	-.064	-.079	-.093	-.106	-.111	-.105	-.090	-.070	-.048	-.027	-.005	.018	.035
Z	.024	.024	.025	.026	.027	.028	.030	.032	.034	.036	.039	.042	.045	.048	.052

DIST.	1.9198	1.9838	2.0478	2.1118	2.1757	2.2397	2.3037
LOC.	30	31	32	33	34	35	36
U	.049	.053	.057	.070	.092	.088	.122
Z	.056	.058	.060	.062	.064	.066	.071

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	.1889	.1888	.1881	.1809	.1206	.0979	.0984	.0998
H	11.3000	11.3265	11.3265	14.8038	24.7568	29.8796	31.7699	33.1790

AT TIME T = 1.51981 SECONDS, AFTER 819 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.1280	.2560	.3840	.5119	.6399	.7679	.8959	1.0239	1.1519	1.2799	1.4078	1.5358	1.6638	1.7918
LOC.	0	2	4	6	8	10	12	14	16	18	20	22	24	26	28
U	.000	-.040	-.067	-.083	-.098	-.112	-.118	-.113	-.100	-.081	-.061	-.041	-.020	.002	.017
Z	.024	.024	.025	.026	.027	.028	.030	.032	.034	.036	.039	.042	.045	.048	.052

DIST.	1.9198	1.9838	2.0478	2.1118	2.1757	2.2397	2.3037
LOC.	30	31	32	33	34	35	36
U	.029	.033	.040	.055	.070	.066	.093
Z	.056	.058	.060	.062	.064	.066	.068

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	.1783	.1763	.1757	.1194	.0943	.0919	.0932	.0947
H	11.3000	11.8291	11.8291	23.6314	28.4522	29.9089	31.4685	33.1790

AT TIME T = 1.53837 SECONDS, AFTER 829 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.1280	.2560	.3840	.5119	.6399	.7679	.8959	1.0239	1.1519	1.2799	1.4078	1.5358	1.6638	1.7918
LOC.	0	2	4	6	8	10	12	14	16	18	20	22	24	26	28
U	.000	-.042	-.070	-.087	-.104	-.119	-.126	-.122	-.110	-.092	-.073	-.055	-.034	-.015	-.001
Z	.024	.024	.025	.026	.027	.028	.030	.032	.034	.036	.039	.042	.045	.048	.052

DIST.	1.9198	1.9838	2.0478	2.1118	2.1757	2.2397	2.3037
LOC.	30	31	32	33	34	35	36
U	.009	.014	.024	.038	.048	.053	.078
Z	.056	.058	.060	.062	.063	.065	.067

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	.0634	.0647	.0645	.0896	.0905	.0896	.0882	.0874
H	11.3000	13.3542	13.3542	26.7703	28.7927	30.0414	31.3603	33.1790

AT TIME T = 1.55692 SECONDS, AFTER 849 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.1280	.2560	.3840	.5119	.6399	.7679	.8959	1.0239	1.1519	1.2799	1.4078	1.5358	1.6638	1.7918
LOC.	0	2	4	6	8	10	12	14	16	18	20	22	24	26	28
U	.000	-.043	-.072	-.091	-.109	-.126	-.133	-.130	-.120	-.103	-.086	-.069	-.049	-.031	-.019
Z	.024	.024	.025	.026	.027	.028	.030	.032	.034	.036	.039	.042	.045	.048	.052

DIST.	1.9198	1.9838	2.0478	2.1118	2.1757	2.2397	2.3037
LOC.	30	31	32	33	34	35	36
U	-.010	-.003	.007	.020	.029	.040	.064
Z	.056	.058	.060	.061	.063	.065	.067

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	-.0005	.0004	.0004	.0356	.0844	.0867	.0839	.0817
H	11.3000	11.5429	11.5429	19.8177	28.3619	30.2434	31.7929	33.1790

AT TIME T = 1.57548 SECONDS, AFTER 849 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.1280	.2560	.3840	.5119	.6399	.7679	.8959	1.0239	1.1519	1.2799	1.4078	1.5358	1.6638	1.7918
LOC.	0	2	4	6	8	10	12	14	16	18	20	22	24	26	28
U	.000	-.045	-.075	-.095	-.115	-.132	-.141	-.139	-.129	-.114	-.098	-.082	-.063	-.048	-.037
Z	.024	.025	.025	.026	.027	.028	.030	.032	.034	.036	.039	.042	.045	.048	.052

DIST.	1.9198	1.9838	2.0478	2.1118	2.1757	2.2397	2.3037
LOC.	30	31	32	33	34	35	36
U	-.028	-.020	-.009	.002	.012	.022	.045
Z	.056	.058	.059	.061	.063	.065	.068

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	-.0071	-.0070	-.0070	-.0041	.0320	.0786	.0802	.0803
H	11.3000	11.3497	11.3497	14.4270	21.2862	30.1146	32.1040	33.1790

AT TIME T = 1.59404 SECONDS, AFTER 859 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.1280	.2560	.3840	.5119	.6399	.7679	.8959	1.0239	1.1519	1.2799	1.4078	1.5358	1.6638	1.7918
LOC.	0	2	4	6	8	10	12	14	16	18	20	22	24	26	28
U	.000	-.046	-.077	-.099	-.120	-.138	-.148	-.147	-.139	-.125	-.111	-.095	-.078	-.064	-.055
Z	.025	.025	.025	.026	.027	.028	.030	.032	.034	.036	.039	.042	.045	.048	.052

DIST.	1.9198	1.9838	2.0478	2.1118	2.1757	2.2397	2.3037
LOC.	30	31	32	33	34	35	36

U	-.045	-.037	-.026	-.015	-.005	.001	.025
Z	.056	.057	.059	.061	.063	.065	.068

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	-.0101	-.0101	-.0100	-.0106	-.0098	.0256	.0751	.0788
H	11.3000	11.3478	11.3478	14.0930	16.1931	23.1648	31.5450	33.1790

AT TIME T = 1.61260 SECONDS, AFTER 869 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.1280	.2560	.3840	.5119	.6399	.7679	.8959	1.0239	1.1519	1.2799	1.4078	1.5358	1.6638	1.7918
LOC.	0	2	4	6	8	10	12	14	16	18	20	22	24	26	28
U	.000	-.047	-.080	-.104	-.126	-.145	-.155	-.155	-.148	-.136	-.123	-.108	-.093	-.081	-.073
Z	.025	.025	.025	.026	.027	.029	.030	.032	.034	.036	.039	.042	.045	.048	.052

DIST.	1.9198	1.9838	2.0478	2.1118	2.1757	2.2397	2.3037
LOC.	30	31	32	33	34	35	36
U	-.062	-.053	-.042	-.032	-.024	-.019	.004
Z	.055	.057	.059	.061	.063	.065	.068

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	-.0140	-.0141	-.0140	-.0157	-.0170	-.0132	.0243	.0699
H	11.3000	11.3723	11.3723	14.3902	15.9682	17.6377	24.3009	33.1790

→ THE DIRECTION OF FLOW AT THE RESERVOIR END OF THE PIPE SYSTEM HAS REVERSED AT TIME T = 1.62837 SECONDS. ←

AT TIME T = 1.63115 SECONDS, AFTER 879 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.1280	.2560	.3840	.5119	.6399	.7679	.8959	1.0239	1.1519	1.2799	1.4078	1.5358	1.6638	1.7918
LOC.	0	2	4	6	8	10	12	14	16	18	20	22	24	26	28
U	.000	-.048	-.082	-.108	-.132	-.151	-.162	-.163	-.157	-.147	-.135	-.121	-.107	-.097	-.090
Z	.025	.025	.025	.026	.027	.029	.030	.032	.034	.036	.039	.042	.045	.048	.052

DIST.	1.9198	1.9838	2.0478	2.1118	2.1757	2.2397	2.3037
LOC.	30	31	32	33	34	35	36
U	-.078	-.069	-.059	-.050	-.043	-.039	-.015
Z	.055	.057	.059	.061	.063	.065	.068

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	-.0208	-.0208	-.0208	-.0204	-.0191	-.0183	-.0183	-.0299
H	11.3000	11.4253	11.4253	14.5249	15.8343	17.1009	19.3257	33.1790

AT TIME T = 1.64971 SECONDS, AFTER 889 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.1280	.2560	.3840	.5119	.6399	.7679	.8959	1.0239	1.1519	1.2799	1.4078	1.5358	1.6638	1.7918

LOC.	0	2	4	6	8	10	12	14	16	18	20	22	24	26	28
U	.000	-.049	-.085	-.112	-.137	-.157	-.169	-.171	-.166	-.158	-.147	-.134	-.122	-.114	-.107
Z	.025	.025	.025	.026	.027	.029	.030	.032	.034	.036	.039	.042	.045	.048	.052

DIST.	1.9198	1.9838	2.0478	2.1118	2.1757	2.2397	2.3037
LOC.	30	31	32	33	34	35	36
U	-.094	-.085	-.076	-.068	-.062	-.058	-.033
Z	.055	.057	.059	.061	.063	.065	.067

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	-.0272	-.0272	-.0271	-.0242	-.0217	-.0242	-.0724	-.1063
H	11.3000	11.3258	11.3258	14.1481	15.6581	17.5199	26.0000	33.1790

AT TIME T = 1.66827 SECONDS, AFTER 899 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.1280	.2560	.3840	.5119	.6399	.7679	.8959	1.0239	1.1519	1.2799	1.4078	1.5358	1.6638	1.7918
LOC.	0	2	4	6	8	10	12	14	16	18	20	22	24	26	28
U	.000	-.050	-.087	-.116	-.143	-.163	-.176	-.179	-.176	-.168	-.159	-.147	-.137	-.130	-.123
Z	.025	.025	.026	.026	.027	.029	.030	.032	.034	.036	.039	.042	.045	.048	.052

DIST.	1.9198	1.9838	2.0478	2.1118	2.1757	2.2397	2.3037
LOC.	30	31	32	33	34	35	36
U	-.110	-.101	-.093	-.086	-.081	-.074	-.050
Z	.055	.057	.059	.061	.063	.065	.067

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	-.0284	-.0284	-.0283	-.0284	-.0293	-.0757	-.1121	-.1150
H	11.3000	11.3249	11.3249	13.7378	15.8326	24.5375	31.4009	33.1790

AT TIME T = 1.68682 SECONDS, AFTER 909 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.1280	.2560	.3840	.5119	.6399	.7679	.8959	1.0239	1.1519	1.2799	1.4078	1.5358	1.6638	1.7918
LOC.	0	2	4	6	8	10	12	14	16	18	20	22	24	26	28
U	.000	-.050	-.090	-.121	-.148	-.170	-.183	-.187	-.185	-.179	-.171	-.161	-.152	-.146	-.139
Z	.025	.025	.026	.026	.028	.029	.030	.032	.034	.036	.039	.042	.045	.048	.052

DIST.	1.9198	1.9838	2.0478	2.1118	2.1757	2.2397	2.3037
LOC.	30	31	32	33	34	35	36
U	-.125	-.117	-.110	-.104	-.098	-.089	-.064
Z	.055	.057	.059	.061	.063	.064	.066

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	-.0298	-.0298	-.0297	-.0334	-.0822	-.1171	-.1183	-.1179
H	11.3000	11.3268	11.3268	14.2852	22.5982	29.7017	31.7650	33.1790

AT TIME T = 1.70538 SECONDS, AFTER 919 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.1280	.2560	.3840	.5119	.6399	.7679	.8959	1.0239	1.1519	1.2799	1.4078	1.5358	1.6638	1.7918
LOC.	0	2	4	6	8	10	12	14	16	18	20	22	24	26	28
U	.000	-.051	-.092	-.125	-.154	-.176	-.189	-.195	-.194	-.190	-.183	-.174	-.167	-.162	-.155
Z	.025	.025	.026	.026	.028	.029	.030	.032	.034	.036	.039	.042	.045	.048	.052

DIST.	1.9198	1.9838	2.0478	2.1118	2.1757	2.2397	2.3037
LOC.	30	31	32	33	34	35	36
U	-.141	-.133	-.127	-.121	-.114	-.101	-.077
Z	.055	.057	.059	.061	.062	.064	.066

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	-.0356	-.0367	-.0366	-.0834	-.1211	-.1249	-.1229	-.1216
H	11.3000	11.5838	11.5838	21.4450	28.1431	29.8333	31.5236	33.1790

AT TIME T = 1.72394 SECONDS, AFTER 929 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.1280	.2560	.3840	.5119	.6399	.7679	.8959	1.0239	1.1519	1.2799	1.4078	1.5358	1.6638	1.7918
LOC.	0	2	4	6	8	10	12	14	16	18	20	22	24	26	28
U	.000	-.051	-.094	-.129	-.159	-.182	-.196	-.203	-.204	-.201	-.195	-.187	-.182	-.178	-.170
Z	.025	.026	.026	.027	.028	.029	.030	.032	.034	.036	.039	.042	.045	.048	.052

DIST.	1.9198	1.9838	2.0478	2.1118	2.1757	2.2397	2.3037
LOC.	30	31	32	33	34	35	36
U	-.157	-.150	-.144	-.137	-.128	-.112	-.088
Z	.055	.057	.059	.061	.062	.064	.065

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	-.1225	-.1234	-.1230	-.1243	-.1261	-.1269	-.1282	-.1279
H	11.3000	13.3604	13.3604	26.7100	28.6886	29.9662	31.2889	33.1790

AT TIME T = 1.74249 SECONDS, AFTER 939 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.1280	.2560	.3840	.5119	.6399	.7679	.8959	1.0239	1.1519	1.2799	1.4078	1.5358	1.6638	1.7918
LOC.	0	2	4	6	8	10	12	14	16	18	20	22	24	26	28
U	.000	-.052	-.097	-.134	-.164	-.188	-.203	-.211	-.213	-.211	-.207	-.201	-.197	-.194	-.186
Z	.026	.026	.026	.027	.028	.029	.031	.032	.034	.036	.039	.042	.045	.048	.052

DIST.	1.9198	1.9838	2.0478	2.1118	2.1757	2.2397	2.3037
LOC.	30	31	32	33	34	35	36
U	-.173	-.166	-.160	-.152	-.141	-.127	-.102
Z	.055	.057	.059	.060	.062	.064	.067

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	-.2133	-.2114	-.2107	-.1658	-.1301	-.1295	-.1319	-.1348
H	11.3000	11.7681	11.7681	21.8961	28.5358	30.1442	31.6630	33.1790

AT TIME T = 1.76105 SECONDS, AFTER 949 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.1280	.2560	.3840	.5119	.6399	.7679	.8959	1.0239	1.1519	1.2799	1.4078	1.5358	1.6638	1.7918
LOC.	0	2	4	6	8	10	12	14	16	18	20	22	24	26	28
U	.000	-.052	-.099	-.138	-.170	-.194	-.210	-.219	-.223	-.222	-.219	-.214	-.212	-.209	-.201
Z	.026	.026	.026	.027	.028	.029	.031	.032	.034	.037	.039	.042	.045	.048	.052

DIST.	1.9198	1.9838	2.0478	2.1118	2.1757	2.2397	2.3037
LOC.	30	31	32	33	34	35	36
U	-.188	-.182	-.176	-.167	-.155	-.149	-.123
Z	.055	.057	.059	.060	.062	.064	.068

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	-.2231	-.2230	-.2223	-.2166	-.1691	-.1351	-.1361	-.1386
H	11.3000	11.3692	11.3692	14.8627	23.3541	30.2334	32.0771	33.1790

AT TIME T = 1.77961 SECONDS, AFTER 959 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.1280	.2560	.3840	.5119	.6399	.7679	.8959	1.0239	1.1519	1.2799	1.4078	1.5358	1.6638	1.7918
LOC.	0	2	4	6	8	10	12	14	16	18	20	22	24	26	28
U	.000	-.053	-.101	-.142	-.175	-.200	-.217	-.227	-.232	-.233	-.231	-.228	-.227	-.224	-.216
Z	.026	.026	.026	.027	.028	.029	.031	.032	.034	.037	.039	.042	.045	.048	.052

DIST.	1.9198	1.9838	2.0478	2.1118	2.1757	2.2397	2.3037
LOC.	30	31	32	33	34	35	36
U	-.204	-.198	-.190	-.181	-.173	-.177	-.150
Z	.055	.057	.059	.060	.062	.064	.070

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	-.2262	-.2262	-.2254	-.2257	-.2217	-.1757	-.1392	-.1373
H	11.3000	11.3494	11.3494	14.0925	16.5508	25.2894	31.7929	33.1790

AT TIME T = 1.79816 SECONDS, AFTER 969 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.1280	.2560	.3840	.5119	.6399	.7679	.8959	1.0239	1.1519	1.2799	1.4078	1.5358	1.6638	1.7918
LOC.	0	2	4	6	8	10	12	14	16	18	20	22	24	26	28
U	.000	-.054	-.104	-.146	-.181	-.206	-.224	-.235	-.242	-.244	-.243	-.242	-.242	-.239	-.230
Z	.026	.026	.026	.027	.028	.029	.031	.032	.034	.037	.039	.042	.045	.048	.052

DIST.	1.9198	1.9838	2.0478	2.1118	2.1757	2.2397	2.3037
LOC.	30	31	32	33	34	35	36
U	-.219	-.213	-.205	-.197	-.195	-.208	-.178
Z	.055	.057	.058	.060	.062	.065	.070

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)

V	-.2298	-.2299	-.2291	-.2305	-.2323	-.2258	-.1769	-.1424
H	11.3000	11.3689	11.3689	14.3138	16.0177	18.1034	26.4348	33.1790

AT TIME T = 1.81672 SECONDS, AFTER 979 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.1280	.2560	.3840	.5119	.6399	.7679	.8959	1.0239	1.1519	1.2799	1.4078	1.5358	1.6638	1.7918
LOC.	0	2	4	6	8	10	12	14	16	18	20	22	24	26	28
U	.000	-.054	-.106	-.151	-.186	-.212	-.231	-.243	-.251	-.254	-.255	-.255	-.256	-.253	-.245
Z	.026	.026	.027	.027	.028	.030	.031	.033	.035	.037	.039	.042	.045	.049	.052

DIST.	1.9198	1.9838	2.0478	2.1118	2.1757	2.2397	2.3037
LOC.	30	31	32	33	34	35	36
U	-.234	-.227	-.220	-.215	-.221	-.237	-.207
Z	.055	.057	.058	.060	.063	.065	.070

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	-.2358	-.2358	-.2351	-.2357	-.2346	-.2336	-.2290	-.2166
H	11.3000	11.4168	11.4168	14.5704	15.8665	17.1563	19.5244	33.1790

AT TIME T = 1.83528 SECONDS, AFTER 989 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.1280	.2560	.3840	.5119	.6399	.7679	.8959	1.0239	1.1519	1.2799	1.4078	1.5358	1.6638	1.7918
LOC.	0	2	4	6	8	10	12	14	16	18	20	22	24	26	28
U	.000	-.055	-.108	-.155	-.191	-.218	-.238	-.252	-.260	-.265	-.267	-.269	-.271	-.267	-.259
Z	.026	.026	.027	.027	.028	.030	.031	.033	.035	.037	.039	.042	.045	.049	.052

DIST.	1.9198	1.9838	2.0478	2.1118	2.1757	2.2397	2.3037
LOC.	30	31	32	33	34	35	36
U	-.248	-.242	-.236	-.237	-.248	-.264	-.233
Z	.055	.057	.059	.061	.063	.066	.070

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	-.2433	-.2431	-.2423	-.2391	-.2370	-.2378	-.2731	-.3155
H	11.3000	11.3702	11.3702	14.2479	15.7102	17.2875	23.9181	33.1790

AT TIME T = 1.85384 SECONDS, AFTER 999 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.1280	.2560	.3840	.5119	.6399	.7679	.8959	1.0239	1.1519	1.2799	1.4078	1.5358	1.6638	1.7918
LOC.	0	2	4	6	8	10	12	14	16	18	20	22	24	26	28
U	.000	-.056	-.111	-.159	-.197	-.225	-.245	-.260	-.270	-.276	-.279	-.283	-.285	-.281	-.273
Z	.027	.027	.027	.028	.029	.030	.031	.033	.035	.037	.040	.042	.046	.049	.052

DIST.	1.9198	1.9838	2.0478	2.1118	2.1757	2.2397	2.3037
LOC.	30	31	32	33	34	35	36
U	-.263	-.257	-.255	-.261	-.274	-.287	-.255
Z	.055	.057	.059	.061	.064	.066	.070

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	-.2446	-.2446	-.2438	-.2435	-.2423	-.2762	-.3240	-.3294
H	11.3000	11.3279	11.3279	13.7911	15.6695	22.4424	30.9519	33.179

AT TIME T = 1.87239 SECONDS, AFTER 1009 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.1280	.2560	.3840	.5119	.6399	.7679	.8959	1.0239	1.1519	1.2799	1.4078	1.5358	1.6638	1.7918
LOC.	0	2	4	6	8	10	12	14	16	18	20	22	24	26	28
U	.000	-.057	-.113	-.163	-.202	-.231	-.252	-.268	-.279	-.286	-.291	-.296	-.298	-.295	-.287
Z	.027	.027	.027	.028	.029	.030	.031	.033	.035	.037	.040	.043	.046	.049	.052

DIST.	1.9198	1.9838	2.0478	2.1118	2.1757	2.2397	2.3037
LOC.	30	31	32	33	34	35	36
U	-.277	-.274	-.276	-.285	-.299	-.306	-.275
Z	.055	.057	.059	.061	.064	.066	.069

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	-.2459	-.2459	-.2450	-.2469	-.2825	-.3282	-.3326	-.3325
H	11.3000	11.3279	11.3279	14.0277	20.4983	29.3040	31.7436	33.1790

AT TIME T = 1.89095 SECONDS, AFTER 1019 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.1280	.2560	.3840	.5119	.6399	.7679	.8959	1.0239	1.1519	1.2799	1.4078	1.5358	1.6638	1.7918
LOC.	0	2	4	6	8	10	12	14	16	18	20	22	24	26	28
U	.000	-.058	-.115	-.167	-.207	-.237	-.259	-.276	-.289	-.297	-.304	-.310	-.312	-.309	-.301
Z	.027	.027	.027	.028	.029	.030	.031	.033	.035	.037	.040	.043	.046	.049	.052

DIST.	1.9198	1.9838	2.0478	2.1118	2.1757	2.2397	2.3037
LOC.	30	31	32	33	34	35	36
U	-.293	-.293	-.298	-.310	-.320	-.320	-.291
Z	.055	.057	.059	.062	.064	.066	.069

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	-.2494	-.2499	-.2491	-.2838	-.3326	-.3388	-.3367	-.3357
H	11.3000	11.4574	11.4574	19.2867	27.6346	29.7982	31.5748	33.1790

AT TIME T = 1.90951 SECONDS, AFTER 1029 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.1280	.2560	.3840	.5119	.6399	.7679	.8959	1.0239	1.1519	1.2799	1.4078	1.5358	1.6638	1.7918
LOC.	0	2	4	6	8	10	12	14	16	18	20	22	24	26	28
U	.000	-.059	-.118	-.171	-.213	-.243	-.267	-.285	-.298	-.307	-.316	-.323	-.325	-.322	-.315
Z	.027	.027	.027	.028	.029	.030	.032	.033	.035	.037	.040	.043	.046	.049	.052

DIST.	1.9198	1.9838	2.0478	2.1118	2.1757	2.2397	2.3037
LOC.	30	31	32	33	34	35	36

U	-.310	-.313	-.321	-.332	-.338	-.332	-.304
Z	.056	.058	.060	.062	.065	.066	.069

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	-.3093	-.3116	-.3135	-.3346	-.3402	-.3411	-.3419	-.341
H	11.3000	13.0638	13.0638	26.3155	28.5840	29.9065	31.2765	33.1790

AT TIME T = 1.92806 SECONDS, AFTER 1039 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.1280	.2560	.3840	.5119	.6399	.7679	.8959	1.0239	1.1519	1.2799	1.4078	1.5358	1.6638	1.7918
LOC.	0	2	4	6	8	10	12	14	16	18	20	22	24	26	28
U	.000	-.060	-.120	-.175	-.218	-.250	-.274	-.293	-.307	-.318	-.328	-.336	-.339	-.335	-.329
Z	.027	.027	.028	.028	.029	.030	.032	.033	.035	.038	.040	.043	.046	.049	.052

DIST.	1.9198	1.9838	2.0478	2.1118	2.1757	2.2397	2.3037
LOC.	30	31	32	33	34	35	36
U	-.328	-.334	-.344	-.352	-.353	-.348	-.319
Z	.056	.058	.060	.063	.065	.066	.071

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	-.4192	-.4167	-.4152	-.3668	-.3431	-.3433	-.3454	-.3482
H	11.3000	12.1458	12.1458	23.6475	28.5887	30.0617	31.5522	33.1790

AT TIME T = 1.94662 SECONDS, AFTER 1049 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.1280	.2560	.3840	.5119	.6399	.7679	.8959	1.0239	1.1519	1.2799	1.4078	1.5358	1.6638	1.7918
LOC.	0	2	4	6	8	10	12	14	16	18	20	22	24	26	28
U	.000	-.061	-.123	-.179	-.223	-.256	-.281	-.301	-.316	-.329	-.341	-.349	-.352	-.349	-.344
Z	.027	.027	.028	.028	.029	.030	.032	.033	.035	.038	.040	.043	.046	.049	.052

DIST.	1.9198	1.9838	2.0478	2.1118	2.1757	2.2397	2.3037
LOC.	30	31	32	33	34	35	36
U	-.347	-.355	-.365	-.370	-.370	-.377	-.344
Z	.056	.058	.061	.063	.065	.067	.074

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	-.4358	-.4357	-.4342	-.4236	-.3698	-.3474	-.3495	-.3497
H	11.3000	11.3997	11.3997	15.7186	25.1366	30.2342	32.0049	33.1790

AT TIME T = 1.96518 SECONDS, AFTER 1059 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.1280	.2560	.3840	.5119	.6399	.7679	.8959	1.0239	1.1519	1.2799	1.4078	1.5358	1.6638	1.7918
LOC.	0	2	4	6	8	10	12	14	16	18	20	22	24	26	28
U	.000	-.062	-.125	-.183	-.229	-.262	-.289	-.309	-.326	-.341	-.353	-.362	-.364	-.362	-.359
Z	.028	.028	.028	.029	.029	.031	.032	.034	.036	.038	.041	.043	.046	.049	.053

DIST.	1.9198	1.9838	2.0478	2.1118	2.1757	2.2397	2.3037
LOC.	30	31	32	33	34	35	36
U	-.367	-.376	-.384	-.388	-.393	-.415	-.377
Z	.056	.059	.061	.063	.065	.068	.075

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	-.4388	-.4388	-.4373	-.4371	-.4277	-.3759	-.3517	-.3508
H	11.3000	11.3578	11.3578	14.1744	17.3844	27.0906	31.9033	33.1790

AT TIME T = 1.98373 SECONDS, AFTER 1069 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.1280	.2560	.3840	.5119	.6399	.7679	.8959	1.0239	1.1519	1.2799	1.4078	1.5358	1.6638	1.7918
LOC.	0	2	4	6	8	10	12	14	16	18	20	22	24	26	28
U	.000	-.063	-.128	-.187	-.234	-.269	-.296	-.317	-.336	-.352	-.366	-.375	-.377	-.375	-.375
Z	.028	.028	.028	.029	.030	.031	.032	.034	.036	.038	.041	.044	.047	.050	.053

DIST.	1.9198	1.9838	2.0478	2.1118	2.1757	2.2397	2.3037
LOC.	30	31	32	33	34	35	36
U	-.388	-.397	-.403	-.409	-.424	-.450	-.410
Z	.057	.059	.061	.063	.066	.069	.075

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	-.4417	-.4418	-.4403	-.4414	-.4432	-.4319	-.3771	-.3537
H	11.3000	11.3729	11.3729	14.2987	16.1354	19.0744	28.3190	33.1790

AT TIME T = 2.00229 SECONDS, AFTER 1079 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.1280	.2560	.3840	.5119	.6399	.7679	.8959	1.0239	1.1519	1.2799	1.4078	1.5358	1.6638	1.7918
LOC.	0	2	4	6	8	10	12	14	16	18	20	22	24	26	28
U	.000	-.065	-.130	-.191	-.239	-.275	-.303	-.326	-.345	-.363	-.378	-.387	-.390	-.389	-.393
Z	.028	.028	.028	.029	.030	.031	.032	.034	.036	.038	.041	.044	.047	.050	.053

DIST.	1.9198	1.9838	2.0478	2.1118	2.1757	2.2397	2.3037
LOC.	30	31	32	33	34	35	36
U	-.408	-.416	-.424	-.436	-.456	-.480	-.439
Z	.057	.059	.062	.064	.067	.070	.073

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	-.4465	-.4466	-.4451	-.4463	-.4456	-.4444	-.4337	-.4033
H	11.3000	11.4138	11.4138	14.6107	15.9865	17.3721	20.4129	33.1790

AT TIME T = 2.02085 SECONDS, AFTER 1089 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.1280	.2560	.3840	.5119	.6399	.7679	.8959	1.0239	1.1519	1.2799	1.4078	1.5358	1.6638	1.7918
LOC.	0	2	4	6	8	10	12	14	16	18	20	22	24	26	28

U	.000	-.066	-.133	-.195	-.244	-.282	-.310	-.334	-.355	-.375	-.390	-.399	-.402	-.411
Z	.028	.028	.029	.029	.030	.031	.032	.034	.036	.039	.041	.044	.047	.050	.053

DIST.	1.9198	1.9838	2.0478	2.1118	2.1757	2.2397	2.3037
LOC.	30	31	32	33	34	35	36
U	-.428	-.437	-.448	-.465	-.485	-.491	-.456
Z	.058	.060	.062	.065	.068	.070	.072

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	-.4538	-.4537	-.4522	-.4493	-.4475	-.4475	-.4704	-.5134
H	11.3000	11.4108	11.4108	14.3797	15.8478	17.3228	22.2716	33.1790

AT TIME T = 2.03940 SECONDS, AFTER 1099 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.1280	.2560	.3840	.5119	.6399	.7679	.8959	1.0239	1.1519	1.2799	1.4078	1.5358	1.6638	1.7918
LOC.	0	2	4	6	8	10	12	14	16	18	20	22	24	26	28
U	.000	-.068	-.136	-.199	-.250	-.288	-.317	-.343	-.366	-.386	-.402	-.412	-.415	-.418	-.429
Z	.028	.028	.029	.029	.030	.031	.033	.034	.036	.039	.041	.044	.047	.050	.054

DIST.	1.9198	1.9838	2.0478	2.1118	2.1757	2.2397	2.3037
LOC.	30	31	32	33	34	35	36
U	-.448	-.459	-.474	-.493	-.504	-.499	-.468
Z	.058	.060	.063	.066	.068	.070	.072

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	-.4556	-.4556	-.4541	-.4533	-.4511	-.4735	-.5270	-.5374
H	11.3000	11.3328	11.3328	13.9271	15.7162	20.7366	30.1073	33.1790

AT TIME T = 2.05796 SECONDS, AFTER 1109 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.1280	.2560	.3840	.5119	.6399	.7679	.8959	1.0239	1.1519	1.2799	1.4078	1.5358	1.6638	1.7918
LOC.	0	2	4	6	8	10	12	14	16	18	20	22	24	26	28
U	.000	-.069	-.138	-.203	-.255	-.294	-.325	-.351	-.376	-.398	-.414	-.424	-.428	-.434	-.448
Z	.029	.029	.029	.030	.030	.031	.033	.035	.037	.039	.042	.044	.047	.050	.054

DIST.	1.9198	1.9838	2.0478	2.1118	2.1757	2.2397	2.3037
LOC.	30	31	32	33	34	35	36
U	-.470	-.484	-.501	-.515	-.517	-.505	-.477
Z	.059	.061	.064	.066	.068	.070	.071

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	-.4565	-.4565	-.4549	-.4559	-.4792	-.5305	-.5403	-.5407
H	11.3000	11.3359	11.3359	13.9471	18.8064	28.4793	31.6749	33.1790

AT TIME T = 2.07652 SECONDS, AFTER 1119 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.1280	.2560	.3840	.5119	.6399	.7679	.8959	1.0239	1.1519	1.2799	1.4078	1.5358	1.6638	1.7918
LOC.	0	2	4	6	8	10	12	14	16	18	20	22	24	26	28
U	.000	-.071	-.141	-.207	-.260	-.301	-.332	-.360	-.386	-.409	-.426	-.436	-.441	-.450	-.468
Z	.029	.029	.029	.030	.030	.032	.033	.035	.037	.039	.042	.045	.048	.051	.055

DIST.	1.9198	1.9838	2.0478	2.1118	2.1757	2.2397	2.3037
LOC.	30	31	32	33	34	35	36
U	-.493	-.509	-.525	-.532	-.527	-.511	-.485
Z	.059	.062	.064	.066	.068	.069	.071

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	-.4585	-.4587	-.4572	-.4807	-.5351	-.5460	-.5441	-.5433
H	11.3000	11.4010	11.4010	17.4818	26.6883	29.7345	31.5942	33.1790

AT TIME T = 2.09508 SECONDS, AFTER 1129 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.1280	.2560	.3840	.5119	.6399	.7679	.8959	1.0239	1.1519	1.2799	1.4078	1.5358	1.6638	1.7918
LOC.	0	2	4	6	8	10	12	14	16	18	20	22	24	26	28
U	.000	-.072	-.144	-.211	-.266	-.307	-.340	-.370	-.397	-.421	-.438	-.448	-.455	-.467	-.488
Z	.029	.029	.029	.030	.031	.032	.033	.035	.037	.039	.042	.045	.048	.051	.055

DIST.	1.9198	1.9838	2.0478	2.1118	2.1757	2.2397	2.3037
LOC.	30	31	32	33	34	35	36
U	-.517	-.533	-.544	-.545	-.533	-.516	-.492
Z	.060	.062	.065	.067	.068	.069	.070

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	-.4968	-.4993	-.4976	-.5363	-.5475	-.5487	-.5489	-.5476
H	11.3000	12.6260	12.6260	25.3979	28.3979	29.8040	31.2817	33.1790

AT TIME T = 2.11363 SECONDS, AFTER 1139 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.1280	.2560	.3840	.5119	.6399	.7679	.8959	1.0239	1.1519	1.2799	1.4078	1.5358	1.6638	1.7918
LOC.	0	2	4	6	8	10	12	14	16	18	20	22	24	26	28
U	.000	-.074	-.146	-.214	-.271	-.313	-.347	-.379	-.408	-.432	-.449	-.460	-.469	-.485	-.509
Z	.029	.029	.030	.030	.031	.032	.033	.035	.037	.040	.042	.045	.048	.052	.056

DIST.	1.9198	1.9838	2.0478	2.1118	2.1757	2.2397	2.3037
LOC.	30	31	32	33	34	35	36
U	-.541	-.554	-.560	-.554	-.539	-.521	-.499
Z	.060	.063	.065	.067	.068	.069	.070

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	-.6116	-.6092	-.6071	-.5642	-.5499	-.5504	-.5522	-.5545
H	11.3000	12.5776	12.5776	24.8170	28.5141	29.9445	31.4307	33.1790

AT TIME T = 2.13219 SECONDS, AFTER 1149 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.1280	.2560	.3840	.5119	.6399	.7679	.8959	1.0239	1.1519	1.2799	1.4078	1.5358	1.6638	1.7918
LOC.	0	2	4	6	8	10	12	14	16	18	20	22	24	26	28
U	.000	-.075	-.149	-.218	-.276	-.319	-.355	-.388	-.418	-.443	-.461	-.473	-.485	-.504	-.532
Z	.029	.030	.030	.030	.031	.032	.034	.035	.038	.040	.043	.045	.048	.052	.056

DIST.	1.9198	1.9838	2.0478	2.1118	2.1757	2.2397
LOC.	30	31	32	33	34	35
U	-.563	-.572	-.572	-.561	-.544	-.525
Z	.061	.063	.065	.066	.068	.069

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	-.6411	-.6408	-.6386	-.6205	-.5671	-.5533	-.5559	-.5567
H	11.3000	11.4443	11.4443	16.9970	26.3724	30.1402	31.8823	33.1790

AT TIME T = 2.15075 SECONDS, AFTER 1159 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.1280	.2560	.3840	.5119	.6399	.7679	.8959	1.0239	1.1519	1.2799	1.4078	1.5358	1.6638	1.7918
LOC.	0	2	4	6	8	10	12	14	16	18	20	22	24	26	28
U	.000	-.077	-.152	-.222	-.281	-.326	-.364	-.398	-.429	-.455	-.473	-.486	-.500	-.523	-.554
Z	.030	.030	.030	.031	.031	.032	.034	.036	.038	.040	.043	.046	.049	.052	.057

DIST.	1.9198	1.9838	2.0478	2.1118	2.1757	2.2397
LOC.	30	31	32	33	34	35
U	-.583	-.587	-.581	-.567	-.549	-.530
Z	.061	.063	.065	.066	.067	.068

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	-.6444	-.6444	-.6422	-.6414	-.6238	-.5725	-.5579	-.5574
H	11.3000	11.3694	11.3694	14.2936	18.6477	28.3178	31.9302	33.1790

AT TIME T = 2.16930 SECONDS, AFTER 1169 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.1280	.2560	.3840	.5119	.6399	.7679	.8959	1.0239	1.1519	1.2799	1.4078	1.5358	1.6638	1.7918
LOC.	0	2	4	6	8	10	12	14	16	18	20	22	24	26	28
U	.000	-.079	-.155	-.226	-.286	-.332	-.372	-.408	-.440	-.466	-.484	-.499	-.517	-.544	-.577
Z	.030	.030	.030	.031	.032	.033	.034	.036	.038	.041	.043	.046	.049	.053	.057

DIST.	1.9198	1.9838	2.0478	2.1118	2.1757	2.2397
LOC.	30	31	32	33	34	35
U	-.599	-.598	-.587	-.571	-.553	-.534
Z	.062	.064	.065	.066	.067	.068

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	-.6467	-.6467	-.6445	-.6454	-.6467	-.6282	-.5740	-.5590
H	11.3000	11.3794	11.3794	14.2968	16.2542	20.4626	29.6657	33.1790

AT TIME T = 2.18786 SECONDS, AFTER 1179 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.1280	.2560	.3840	.5119	.6399	.7679	.8959	1.0239	1.1519	1.2799	1.4078	1.5358	1.6638	1.7918
LOC.	0	2	4	6	8	10	12	14	16	18	20	22	24	26	28
U	.000	-.080	-.158	-.230	-.291	-.339	-.381	-.418	-.451	-.477	-.496	-.513	-.535	-.565	-.598
Z	.030	.030	.031	.031	.032	.033	.034	.036	.038	.041	.043	.046	.050	.054	.058

DIST.	1.9198	1.9838	2.0478	2.1118	2.1757
LOC.	30	31	32	33	34
U	-.612	-.606	-.593	-.576	-.557
Z	.062	.064	.065	.066	.067

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	-.6505	-.6506	-.6484	-.6499	-.6498	-.6480	-.6291	-.5904
H	11.3000	11.4136	11.4136	14.6165	16.1107	17.6190	21.7788	33.1795

AT TIME T = 2.20642 SECONDS, AFTER 1189 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.1280	.2560	.3840	.5119	.6399	.7679	.8959	1.0239	1.1519	1.2799	1.4078	1.5358	1.6638	1.7918
LOC.	0	2	4	6	8	10	12	14	16	18	20	22	24	26	28
U	.000	-.082	-.161	-.234	-.296	-.346	-.389	-.428	-.462	-.489	-.509	-.528	-.553	-.587	-.618
Z	.030	.031	.031	.031	.032	.033	.035	.036	.039	.041	.044	.047	.050	.054	.059

DIST.	1.9198	1.9838	2.0478	2.1118	2.1757
LOC.	30	31	32	33	34
U	-.623	-.613	-.597	-.579	-.560
Z	.062	.064	.065	.066	.067

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	-.6571	-.6570	-.6548	-.6527	-.6512	-.6508	-.6642	-.6989
H	11.3000	11.4375	11.4375	14.5052	15.9816	17.4266	21.1833	33.1790

AT TIME T = 2.22497 SECONDS, AFTER 1199 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.1280	.2560	.3840	.5119	.6399	.7679	.8959	1.0239	1.1519	1.2799	1.4078	1.5358	1.6638	1.7918
LOC.	0	2	4	6	8	10	12	14	16	18	20	22	24	26	28
U	.000	-.084	-.164	-.238	-.301	-.353	-.398	-.439	-.473	-.500	-.521	-.543	-.573	-.608	-.635
Z	.031	.031	.031	.032	.032	.033	.035	.037	.039	.041	.044	.047	.051	.055	.059

DIST.	1.9198	1.9838	2.0478	2.1118	2.1757
LOC.	30	31	32	33	34
U	-.631	-.618	-.601	-.583	-.564
Z	.062	.063	.064	.065	.066

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)

V	-.6598	-.6598	-.6575	-.6561	-.6537	-.6673	-.7203	-.7379
H	11.3000	11.3434	11.3434	14.0820	15.8217	19.5380	28.8432	33.1790

AT TIME T = 2.24353 SECONDS, AFTER 1209 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.1280	.2560	.3840	.5119	.6399	.7679	.8959	1.0239	1.1519	1.2799	1.4078	1.5358	1.6638	1.7918
LOC.	0	2	4	6	8	10	12	14	16	18	20	22	24	26	28
U	.000	-.085	-.167	-.242	-.306	-.360	-.408	-.449	-.484	-.511	-.534	-.560	-.593	-.629	-.649
Z	.031	.031	.031	.032	.032	.034	.035	.037	.039	.042	.044	.047	.051	.055	.059

DIST.	1.9198	1.9838	2.0478	2.1118
LOC.	30	31	32	33
U	-.637	-.622	-.605	-.586
Z	.062	.063	.064	.065

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	-.6602	-.6602	-.6580	-.6585	-.6722	-.7230	-.7408	-.7417
H	11.3000	11.3476	11.3476	13.9383	17.6319	27.2133	31.5558	33.1790

AT TIME T = 2.26209 SECONDS, AFTER 1219 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.1280	.2560	.3840	.5119	.6399	.7679	.8959	1.0239	1.1519	1.2799	1.4078	1.5358	1.6638	1.7918
LOC.	0	2	4	6	8	10	12	14	16	18	20	22	24	26	28
U	.000	-.087	-.170	-.246	-.311	-.368	-.417	-.459	-.495	-.523	-.548	-.577	-.613	-.648	-.668
Z	.031	.031	.032	.032	.033	.034	.035	.037	.040	.042	.045	.048	.052	.056	.060

DIST.	1.9198	1.9838	2.0478	2.1118
LOC.	30	31	32	33
U	-.642	-.626	-.608	-.589
Z	.062	.063	.064	.065

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	-.6612	-.6614	-.6592	-.6740	-.7277	-.7455	-.7444	-.7437
H	11.3000	11.3800	11.3800	16.1671	25.3051	29.6309	31.5895	33.1790

AT TIME T = 2.28064 SECONDS, AFTER 1229 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.1280	.2560	.3840	.5119	.6399	.7679	.8959	1.0239	1.1519	1.2799	1.4078	1.5358	1.6638	1.7918
LOC.	0	2	4	6	8	10	12	14	16	18	20	22	24	26	28
U	.000	-.088	-.173	-.250	-.317	-.376	-.426	-.470	-.506	-.535	-.563	-.595	-.634	-.666	-.676
Z	.032	.032	.032	.032	.033	.034	.036	.038	.040	.042	.045	.048	.052	.057	.060

DIST.	1.9198	1.9838	2.0478	2.1118
LOC.	30	31	32	33
U	-.646	-.629	-.611	-.592
Z	.062	.063	.064	.065

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	-.6842	-.6864	-.6840	-.7282	-.7472	-.7490	-.7484	-.7471
H	11.3000	12.2208	12.2208	23.9988	28.1455	29.6797	31.2974	33.1790

AT TIME T = 2.29920 SECONDS, AFTER 1239 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.1280	.2560	.3840	.5119	.6399	.7679	.8959	1.0239	1.1519	1.2799	1.4078	1.5358	1.6638	1.7918
LOC.	0	2	4	6	8	10	12	14	16	18	20	22	24	26	28
U	.000	-.090	-.176	-.254	-.322	-.383	-.436	-.481	-.517	-.548	-.578	-.615	-.655	-.681	-.677
Z	.032	.032	.032	.033	.033	.034	.036	.038	.040	.043	.046	.049	.053	.057	.060

DIST.	1.9198	1.9838	2.0478
LOC.	30	31	32
U	-.649	-.632	-.614
Z	.062	.063	.064

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	-.7906	-.7891	-.7865	-.7570	-.7495	-.7501	-.7517	-.7531
H	11.3000	12.9027	12.9027	25.4628	28.3708	29.8115	31.3115	33.1790

AT TIME T = 2.31776 SECONDS, AFTER 1249 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.1280	.2560	.3840	.5119	.6399	.7679	.8959	1.0239	1.1519	1.2799	1.4078	1.5358	1.6638	1.7918
LOC.	0	2	4	6	8	10	12	14	16	18	20	22	24	26	28
U	.000	-.092	-.178	-.258	-.328	-.392	-.446	-.491	-.528	-.561	-.594	-.634	-.674	-.693	-.682
Z	.032	.032	.033	.033	.034	.035	.036	.038	.041	.043	.046	.050	.054	.057	.060

DIST.	1.9198	1.9838	2.0478
LOC.	30	31	32
U	-.652	-.634	-.616
Z	.062	.063	.064

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	-.8380	-.8372	-.8344	-.8076	-.7599	-.7522	-.7548	-.7562
H	11.3000	11.5367	11.5367	18.5778	27.1348	30.0018	31.7335	33.1790

AT TIME T = 2.33632 SECONDS, AFTER 1259 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.1280	.2560	.3840	.5119	.6399	.7679	.8959	1.0239	1.1519	1.2799	1.4078	1.5358	1.6638	1.7918
LOC.	0	2	4	6	8	10	12	14	16	18	20	22	24	26	28
U	.000	-.093	-.181	-.262	-.334	-.400	-.456	-.502	-.540	-.574	-.612	-.655	-.691	-.703	-.687
Z	.033	.033	.033	.033	.034	.035	.037	.039	.041	.043	.047	.050	.054	.058	.060

DIST.	1.9198	1.9838
LOC.	30	31

U	-.655	-.637
Z	.062	.063

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	-.8419	-.8418	-.8390	-.8371	-.8101	-.7645	-.7567	-.7564
H	11.3000	11.3862	11.3862	14.5126	20.2363	29.0617	31.9103	33.1790

AT TIME T = 2.35487 SECONDS, AFTER 1269 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.1280	.2560	.3840	.5119	.6399	.7679	.8959	1.0239	1.1519	1.2799	1.4078	1.5358	1.6638	1.7918
LOC.	0	2	4	6	8	10	12	14	16	18	20	22	24	26	28
U	.000	-.095	-.184	-.266	-.341	-.408	-.466	-.513	-.552	-.589	-.630	-.674	-.707	-.711	-.690
Z	.033	.033	.033	.034	.034	.035	.037	.039	.041	.044	.047	.051	.055	.058	.060

DIST.	1.9198	1.9838
LOC.	30	31
U	-.657	-.639
Z	.062	.062

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	-.8436	-.8436	-.8407	-.8414	-.8414	-.8144	-.7661	-.7572
H	11.3000	11.3881	11.3881	14.3262	16.4645	22.1720	30.5557	33.1790

AT TIME T = 2.37343 SECONDS, AFTER 1279 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.1280	.2560	.3840	.5119	.6399	.7679	.8959	1.0239	1.1519	1.2799	1.4078	1.5358	1.6638	1.7918
LOC.	0	2	4	6	8	10	12	14	16	18	20	22	24	26	28
U	.000	-.096	-.187	-.271	-.347	-.417	-.476	-.524	-.564	-.604	-.649	-.693	-.720	-.717	-.693
Z	.033	.033	.034	.034	.034	.036	.037	.039	.042	.044	.048	.051	.055	.058	.060

DIST.	1.9198
LOC.	30
U	-.659
Z	.061

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	-.8464	-.8465	-.8436	-.8451	-.8457	-.8429	-.8147	-.7757
H	11.3000	11.4159	11.4159	14.6162	16.2652	17.9853	23.5111	33.1790

AT TIME T = 2.39199 SECONDS, AFTER 1289 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.1280	.2560	.3840	.5119	.6399	.7679	.8959	1.0239	1.1519	1.2799	1.4078	1.5358	1.6638	1.7918
LOC.	0	2	4	6	8	10	12	14	16	18	20	22	24	26	28
U	.000	-.097	-.190	-.275	-.354	-.426	-.486	-.535	-.578	-.621	-.668	-.711	-.731	-.722	-.695
Z	.034	.034	.034	.034	.035	.036	.038	.040	.042	.045	.048	.052	.055	.058	.060

DIST.	1.9198
LOC.	30
U	-.660
Z	.061

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	-.8519	-.8519	-.8490	-.8479	-.8465	-.8459	-.8522	-.8718
H	11.3000	11.4521	11.4521	14.6320	16.1370	17.6091	20.6720	33.1790

AT TIME T = 2.41054 SECONDS, AFTER 1299 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.0640	.1280	.1920	.2560	.3200	.3840	.4479	.5119	.5759	.6399	.7039	.7679	.8319	.8959
LOC.	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
U	.000	-.050	-.099	-.147	-.193	-.237	-.280	-.321	-.361	-.399	-.435	-.467	-.496	-.523	-.547
Z	.034	.034	.034	.034	.034	.034	.034	.035	.035	.036	.036	.037	.038	.039	.040

DIST.	.9599	1.0239	1.0879	1.1519	1.2159	1.2799	1.3438	1.4078	1.4718	1.5358	1.5998	1.6638	1.7278	1.7918	1.8558
LOC.	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29
U	-.569	-.591	-.614	-.638	-.663	-.688	-.710	-.727	-.737	-.740	-.736	-.726	-.712	-.696	-.679
Z	.041	.042	.044	.045	.047	.049	.051	.053	.054	.056	.057	.058	.059	.060	.060

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	-.8555	-.8554	-.8525	-.8504	-.8481	-.8558	-.9028	-.9284
H	11.3000	11.3669	11.3669	14.2522	15.9768	18.8183	27.2958	33.1790

AT TIME T = 2.42910 SECONDS, AFTER 1309 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.0640	.1280	.1920	.2560	.3200	.3840	.4479	.5119	.5759	.6399	.7039	.7679	.8319	.8959
LOC.	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
U	.000	-.051	-.100	-.149	-.196	-.241	-.284	-.327	-.368	-.407	-.444	-.477	-.507	-.534	-.559
Z	.034	.034	.034	.034	.035	.035	.035	.035	.036	.036	.037	.038	.038	.039	.040

DIST.	.9599	1.0239	1.0879	1.1519	1.2159	1.2799	1.3438	1.4078	1.4718	1.5358	1.5998	1.6638	1.7278	1.7918	1.8558
LOC.	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29
U	-.582	-.606	-.631	-.656	-.682	-.706	-.727	-.741	-.748	-.747	-.740	-.728	-.714	-.698	-.681
Z	.042	.043	.044	.046	.048	.050	.051	.053	.055	.056	.057	.058	.059	.059	.060

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	-.8554	-.8554	-.8525	-.8527	-.8597	-.9048	-.9318	-.9337
H	11.3000	11.3609	11.3609	13.9909	16.9296	25.6358	31.3362	33.1790

AT TIME T = 2.44766 SECONDS, AFTER 1319 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.0640	.1280	.1920	.2560	.3200	.3840	.4479	.5119	.5759	.6399	.7039	.7679	.8319	.8959
LOC.	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14

U	.000	-.051	-.102	-.151	-.199	-.245	-.289	-.333	-.376	-.416	-.453	-.487	-.518	-.545	-.571
Z	.035	.035	.035	.035	.035	.035	.035	.036	.036	.036	.037	.038	.039	.040	.041

DIST.	.9599	1.0239	1.0879	1.1519	1.2159	1.2799	1.3438	1.4078	1.4718	1.5358	1.5998	1.6638	1.7278	1.7918	1.8558
LOC.	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29
U	-.596	-.622	-.648	-.675	-.701	-.724	-.742	-.753	-.756	-.752	-.743	-.730	-.715	-.699	-.682
Z	.042	.043	.045	.047	.048	.050	.052	.053	.055	.056	.057	.058	.059	.059	.060

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	-.8556	-.8557	-.8528	-.8617	-.9091	-.9354	-.9356	-.9352
H	11.3000	11.3765	11.3765	15.3105	23.6230	29.4179	31.5529	33.1790

AT TIME T = 2.46621 SECONDS, AFTER 1329 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.0640	.1280	.1920	.2560	.3200	.3840	.4479	.5119	.5759	.6399	.7039	.7679	.8319	.8959
LOC.	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
U	.000	-.052	-.103	-.153	-.202	-.249	-.295	-.339	-.383	-.424	-.463	-.497	-.529	-.557	-.584
Z	.035	.035	.035	.035	.035	.035	.036	.036	.036	.037	.038	.038	.039	.040	.041

DIST.	.9599	1.0239	1.0879	1.1519	1.2159	1.2799	1.3438	1.4078	1.4718	1.5358	1.5998	1.6638	1.7278	1.7918
LOC.	15	16	17	18	19	20	21	22	23	24	25	26	27	28
U	-.611	-.638	-.666	-.694	-.719	-.741	-.756	-.763	-.763	-.756	-.746	-.732	-.716	-.700
Z	.043	.044	.046	.047	.049	.051	.052	.054	.055	.056	.057	.058	.058	.059

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	-.8685	-.8700	-.8671	-.9091	-.9372	-.9399	-.9388	-.9375
H	11.3000	11.9074	11.9074	22.2577	27.7677	29.5328	31.3038	33.1790

AT TIME T = 2.48477 SECONDS, AFTER 1339 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.0640	.1280	.1920	.2560	.3200	.3840	.4479	.5119	.5759	.6399	.7039	.7679	.8319	.8959
LOC.	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
U	.000	-.052	-.104	-.155	-.205	-.253	-.300	-.346	-.391	-.433	-.472	-.508	-.540	-.570	-.598
Z	.036	.036	.036	.036	.036	.036	.036	.036	.037	.037	.038	.039	.040	.041	.042

DIST.	.9599	1.0239	1.0879	1.1519	1.2159	1.2799	1.3438	1.4078	1.4718	1.5358	1.5998	1.6638	1.7278	1.7918
LOC.	15	16	17	18	19	20	21	22	23	24	25	26	27	28
U	-.627	-.655	-.684	-.712	-.737	-.756	-.767	-.771	-.768	-.759	-.747	-.733	-.717	-.701
Z	.043	.045	.046	.048	.050	.051	.053	.054	.055	.056	.057	.058	.058	.059

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	-.9573	-.9571	-.9539	-.9423	-.9398	-.9405	-.9418	-.9423
H	11.3000	13.0125	13.0125	25.6151	28.1583	29.6531	31.2018	33.1790

AT TIME T = 2.50333 SECONDS, AFTER 1349 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.0640	.1280	.1920	.2560	.3200	.3840	.4479	.5119	.5759	.6399	.7039	.7679	.8319	.8959
LOC.	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
U	.000	-.053	-.106	-.158	-.208	-.258	-.306	-.353	-.399	-.442	-.482	-.518	-.552	-.583	-.613
Z	.036	.036	.036	.036	.036	.036	.036	.037	.037	.038	.038	.039	.040	.041	.042

DIST.	.9599	1.0239	1.0879	1.1519	1.2159	1.2799	1.3438	1.4078	1.4718	1.5358	1.5998	1.6638	1.7278
LOC.	15	16	17	18	19	20	21	22	23	24	25	26	27
U	-.643	-.673	-.703	-.730	-.753	-.768	-.776	-.777	-.771	-.761	-.749	-.734	-.718
Z	.044	.045	.047	.049	.050	.052	.053	.054	.055	.056	.057	.058	.058

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	-1.0232	-1.0219	-1.0185	-.9843	-.9457	-.9417	-.9441	-.9460
H	11.3000	11.7135	11.7135	20.2098	27.5041	29.8263	31.5689	33.1790

AT TIME T = 2.52188 SECONDS, AFTER 1359 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.0640	.1280	.1920	.2560	.3200	.3840	.4479	.5119	.5759	.6399	.7039	.7679	.8319	.8959
LOC.	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
U	.000	-.054	-.107	-.160	-.212	-.263	-.312	-.360	-.407	-.451	-.492	-.530	-.564	-.597	-.629
Z	.036	.036	.036	.036	.036	.037	.037	.037	.038	.038	.039	.040	.041	.042	.043

DIST.	.9599	1.0239	1.0879	1.1519	1.2159	1.2799	1.3438	1.4078	1.4718	1.5358	1.5998	1.6638	1.7278
LOC.	15	16	17	18	19	20	21	22	23	24	25	26	27
U	-.660	-.692	-.721	-.747	-.767	-.779	-.783	-.781	-.774	-.763	-.749	-.734	-.718
Z	.044	.046	.048	.049	.051	.052	.053	.054	.055	.056	.057	.057	.058

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	-1.0291	-1.0290	-1.0256	-1.0215	-.9860	-.9492	-.9459	-.9458
H	11.3000	11.4079	11.4079	14.9158	21.9053	29.4225	31.8437	33.1790

AT TIME T = 2.54044 SECONDS, AFTER 1369 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.0640	.1280	.1920	.2560	.3200	.3840	.4479	.5119	.5759	.6399	.7039	.7679	.8319	.8959
LOC.	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
U	.000	-.054	-.109	-.162	-.215	-.267	-.318	-.368	-.416	-.461	-.502	-.541	-.577	-.611	-.645
Z	.037	.037	.037	.037	.037	.037	.037	.038	.038	.039	.039	.040	.041	.042	.043

DIST.	.9599	1.0239	1.0879	1.1519	1.2159	1.2799	1.3438	1.4078	1.4718	1.5358	1.5998	1.6638
LOC.	15	16	17	18	19	20	21	22	23	24	25	26
U	-.678	-.710	-.739	-.762	-.779	-.788	-.789	-.785	-.776	-.764	-.750	-.734
Z	.045	.047	.048	.050	.051	.052	.054	.054	.055	.056	.057	.057

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	-1.0302	-1.0302	-1.0268	-1.0272	-1.0248	-.9900	-.9509	-.9458
H	11.3000	11.3991	11.3991	14.3929	16.8689	23.9492	31.0785	33.1790

AT TIME T = 2.55900 SECONDS, AFTER 1379 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.0640	.1280	.1920	.2560	.3200	.3840	.4479	.5119	.5759	.6399	.7039	.7679	.8319	.8959
LOC.	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
U	.000	-.055	-.110	-.165	-.219	-.272	-.324	-.375	-.424	-.470	-.513	-.553	-.591	-.627	-.662
Z	.037	.037	.037	.037	.037	.037	.038	.038	.039	.039	.040	.041	.042	.043	.044

DIST.	.9599	1.0239	1.0879	1.1519	1.2159	1.2799	1.3438	1.4078	1.4718	1.5358	1.5998
LOC.	15	16	17	18	19	20	21	22	23	24	25
U	-.696	-.728	-.755	-.776	-.789	-.794	-.793	-.787	-.777	-.764	-.750
Z	.046	.047	.049	.050	.052	.053	.054	.055	.055	.056	.057

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	-1.0321	-1.0321	-1.0286	-1.0300	-1.0311	-1.0262	-.9897	-.9559
H	11.3000	11.4213	11.4213	14.6286	16.4476	18.5609	25.3549	33.1790

AT TIME T = 2.57756 SECONDS, AFTER 1389 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.0640	.1280	.1920	.2560	.3200	.3840	.4479	.5119	.5759	.6399	.7039	.7679	.8319	.8959
LOC.	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
U	.000	-.056	-.112	-.168	-.223	-.278	-.331	-.383	-.433	-.480	-.524	-.566	-.605	-.643	-.680
Z	.038	.038	.038	.038	.038	.038	.038	.039	.039	.040	.040	.041	.042	.043	.045

DIST.	.9599	1.0239	1.0879	1.1519	1.2159	1.2799	1.3438	1.4078	1.4718	1.5358	1.5998
LOC.	15	16	17	18	19	20	21	22	23	24	25
U	-.715	-.745	-.770	-.788	-.797	-.800	-.796	-.788	-.777	-.764	-.749
Z	.046	.048	.049	.051	.052	.053	.054	.055	.055	.056	.057

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	-1.0363	-1.0363	-1.0328	-1.0326	-1.0314	-1.0307	-1.0310	-1.0333
H	11.3000	11.4606	11.4606	14.7526	16.3205	17.8663	20.7364	33.1790

AT TIME T = 2.59611 SECONDS, AFTER 1399 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.0640	.1280	.1920	.2560	.3200	.3840	.4479	.5119	.5759	.6399	.7039	.7679	.8319	.8959
LOC.	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
U	.000	-.057	-.113	-.170	-.227	-.283	-.338	-.391	-.442	-.491	-.536	-.580	-.621	-.660	-.698
Z	.038	.038	.038	.038	.038	.038	.039	.039	.040	.040	.041	.042	.043	.044	.045

DIST.	.9599	1.0239	1.0879	1.1519	1.2159	1.2799	1.3438	1.4078	1.4718	1.5358
LOC.	15	16	17	18	19	20	21	22	23	24
U	-.732	-.761	-.783	-.797	-.804	-.803	-.798	-.789	-.777	-.764
Z	.047	.048	.050	.051	.052	.053	.054	.055	.055	.056

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	-1.0402	-1.0401	-1.0366	-1.0342	-1.0321	-1.0361	-1.0739	-1.1055
H	11.3000	11.4010	11.4010	14.4315	16.1723	18.4930	25.7190	33.1790

AT TIME T = 2.61467 SECONDS, AFTER 1409 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.0640	.1280	.1920	.2560	.3200	.3840	.4479	.5119	.5759	.6399	.7039	.7679	.8319	.8959
LOC.	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
U	.000	-.057	-.115	-.173	-.232	-.289	-.345	-.400	-.452	-.502	-.549	-.594	-.637	-.678	-.716
Z	.039	.039	.039	.039	.039	.039	.039	.040	.040	.041	.041	.042	.043	.045	.046

DIST.	.9599	1.0239	1.0879	1.1519	1.2159	1.2799	1.3438	1.4078	1.4718	1.5358
LOC.	15	16	17	18	19	20	21	22	23	24
U	-.749	-.775	-.794	-.805	-.808	-.806	-.799	-.789	-.777	-.763
Z	.048	.049	.050	.051	.052	.053	.054	.055	.055	.056

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	-1.0397	-1.0397	-1.0362	-1.0362	-1.0389	-1.0752	-1.1104	-1.1144
H	11.3000	11.3745	11.3745	14.1007	16.6021	23.9989	30.9378	33.1790

AT TIME T = 2.63323 SECONDS, AFTER 1419 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.0640	.1280	.1920	.2560	.3200	.3840	.4479	.5119	.5759	.6399	.7039	.7679	.8319	.8959
LOC.	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
U	.000	-.058	-.117	-.177	-.236	-.295	-.352	-.408	-.462	-.513	-.562	-.609	-.654	-.696	-.733
Z	.039	.039	.039	.039	.039	.039	.040	.040	.041	.041	.042	.043	.044	.045	.047

DIST.	.9599	1.0239	1.0879	1.1519	1.2159	1.2799	1.3438	1.4078	1.4718
LOC.	15	16	17	18	19	20	21	22	23
U	-.764	-.788	-.803	-.811	-.812	-.808	-.800	-.789	-.777
Z	.048	.049	.051	.052	.053	.053	.054	.054	.055

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	-1.0393	-1.0394	-1.0359	-1.0409	-1.0790	-1.1129	-1.1155	-1.1153
H	11.3000	11.3828	11.3828	14.8199	21.9025	29.0082	31.4830	33.1790

AT TIME T = 2.65178 SECONDS, AFTER 1429 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.0640	.1280	.1920	.2560	.3200	.3840	.4479	.5119	.5759	.6399	.7039	.7679	.8319	.8959
LOC.	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
U	.000	-.059	-.119	-.180	-.241	-.301	-.360	-.417	-.472	-.525	-.576	-.625	-.671	-.713	-.749
Z	.040	.040	.040	.040	.040	.040	.040	.041	.041	.042	.043	.044	.045	.046	.047

DIST.	.9599	1.0239	1.0879	1.1519	1.2159	1.2799	1.3438	1.4078	1.4718
LOC.	15	16	17	18	19	20	21	22	23
U	-.778	-.799	-.811	-.815	-.814	-.809	-.800	-.789	-.776
Z	.049	.050	.051	.052	.053	.053	.054	.054	.055

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)

V	-1.0458	-1.0468	-1.0433	-1.0786	-1.1146	-1.1192	-1.1177	-1.1167
H	11.3000	11.6970	11.6970	20.4353	27.1862	29.3701	31.2915	33.1790

AT TIME T = 2.67034 SECONDS, AFTER 1439 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.0640	.1280	.1920	.2560	.3200	.3840	.4479	.5119	.5759	.6399	.7039	.7679	.8319	.8959
LOC.	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
U	.000	-.061	-.122	-.184	-.246	-.307	-.368	-.426	-.483	-.538	-.591	-.641	-.688	-.730	-.764
Z	.040	.040	.040	.040	.040	.041	.041	.041	.042	.042	.043	.044	.045	.047	.048

DIST.	.9599	1.0239	1.0879	1.1519	1.2159	1.2799	1.3438	1.4078
LOC.	15	16	17	18	19	20	21	22
U	-.790	-.807	-.816	-.819	-.816	-.809	-.799	-.788
Z	.049	.050	.051	.052	.053	.053	.054	.054

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	-1.1135	-1.1143	-1.1186	-1.1167	-1.1186	-1.1194	-1.1203	-1.1201
H	11.3000	12.9682	12.9682	25.3832	27.6836	29.4664	31.1096	33.1790

AT TIME T = 2.68890 SECONDS, AFTER 1449 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.0640	.1280	.1920	.2560	.3200	.3840	.4479	.5119	.5759	.6399	.7039	.7679	.8319	.8959
LOC.	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
U	.000	-.062	-.124	-.188	-.251	-.314	-.376	-.436	-.495	-.552	-.607	-.658	-.705	-.746	-.777
Z	.041	.041	.041	.041	.041	.041	.041	.042	.042	.043	.044	.045	.046	.047	.049

DIST.	.9599	1.0239	1.0879	1.1519	1.2159	1.2799	1.3438	1.4078
LOC.	15	16	17	18	19	20	21	22
U	-.800	-.814	-.820	-.821	-.816	-.809	-.798	-.786
Z	.050	.051	.051	.052	.053	.053	.054	.054

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	-1.1935	-1.1918	-1.1878	-1.1503	-1.1215	-1.1197	-1.1218	-1.1239
H	11.3000	11.9708	11.9708	21.6408	27.5861	29.6221	31.3970	33.1790

AT TIME T = 2.70745 SECONDS, AFTER 1459 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.0640	.1280	.1920	.2560	.3200	.3840	.4479	.5119	.5759	.6399	.7039	.7679	.8319	.8959
LOC.	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
U	.000	-.063	-.127	-.192	-.257	-.321	-.385	-.447	-.507	-.566	-.623	-.675	-.722	-.760	-.789
Z	.041	.041	.041	.042	.042	.042	.042	.043	.043	.044	.045	.046	.047	.048	.049

DIST.	.9599	1.0239	1.0879	1.1519	1.2159	1.2799	1.3438
LOC.	15	16	17	18	19	20	21
U	-.808	-.819	-.823	-.822	-.816	-.808	-.797
Z	.050	.051	.052	.052	.053	.053	.054

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	-1.2040	-1.2039	-1.1998	-1.1922	-1.1512	-1.1239	-1.1233	-1.1235
H	11.3000	11.4340	11.4340	15.5735	23.4037	29.5156	31.7310	33.1790

AT TIME T = 2.72601 SECONDS, AFTER 1469 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.0640	.1280	.1920	.2560	.3200	.3840	.4479	.5119	.5759	.6399	.7039	.7679	.8319	.8959
LOC.	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
U	.000	-.065	-.130	-.196	-.262	-.328	-.394	-.458	-.521	-.581	-.639	-.692	-.737	-.773	-.798
Z	.042	.042	.042	.042	.042	.042	.043	.043	.044	.045	.045	.046	.048	.049	.050

DIST.	.9599	1.0239	1.0879	1.1519	1.2159	1.2799	1.3438
LOC.	15	16	17	18	19	20	21
U	-.815	-.823	-.825	-.822	-.816	-.807	-.796
Z	.050	.051	.052	.052	.053	.053	.054

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	-1.2046	-1.2046	-1.2005	-1.2006	-1.1943	-1.1547	-1.1255	-1.1227
H	11.3000	11.4117	11.4117	14.4963	17.5449	25.5356	31.3413	33.1790

AT TIME T = 2.74457 SECONDS, AFTER 1479 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.0640	.1280	.1920	.2560	.3200	.3840	.4479	.5119	.5759	.6399	.7039	.7679	.8319	.8959
LOC.	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
U	.000	-.066	-.133	-.201	-.268	-.336	-.403	-.470	-.534	-.597	-.655	-.707	-.750	-.783	-.806
Z	.043	.043	.043	.043	.043	.043	.043	.044	.045	.045	.046	.047	.048	.049	.050

DIST.	.9599	1.0239	1.0879	1.1519	1.2159	1.2799
LOC.	15	16	17	18	19	20
U	-.820	-.826	-.826	-.822	-.815	-.805
Z	.051	.051	.052	.052	.053	.053

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	-1.2055	-1.2055	-1.2014	-1.2026	-1.2039	-1.1956	-1.1539	-1.1275
H	11.3000	11.4288	11.4288	14.6608	16.6484	19.4132	27.0511	33.1790

AT TIME T = 2.76312 SECONDS, AFTER 1489 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.0640	.1280	.1920	.2560	.3200	.3840	.4479	.5119	.5759	.6399	.7039	.7679	.8319	.8959
LOC.	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
U	.000	-.068	-.136	-.206	-.275	-.344	-.414	-.482	-.549	-.613	-.671	-.722	-.762	-.792	-.812
Z	.043	.043	.043	.043	.044	.044	.044	.045	.045	.046	.047	.048	.049	.050	.050

DIST.	.9599	1.0239	1.0879	1.1519	1.2159
LOC.	15	16	17	18	19

U	-.823	-.827	-.826	-.821	-.813
Z	.051	.051	.052	.052	.053

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	-1.2083	-1.2083	-1.2042	-1.2047	-1.2039	-1.2029	-1.1973	-1.1847
H	11.3000	11.4657	11.4657	14.8578	16.5296	18.1865	21.3343	33.1790

AT TIME T = 2.78168 SECONDS, AFTER 1499 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.0640	.1280	.1920	.2560	.3200	.3840	.4479	.5119	.5759	.6399	.7039	.7679	.8319	.8959
LOC.	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
U	.000	-.070	-.140	-.211	-.282	-.353	-.425	-.495	-.564	-.628	-.686	-.735	-.773	-.800	-.817
Z	.044	.044	.044	.044	.044	.045	.045	.046	.046	.047	.048	.049	.049	.050	.051

DIST.	.9599	1.0239	1.0879	1.1519	1.2159
LOC.	15	16	17	18	19
U	-.825	-.828	-.825	-.820	-.811
Z	.051	.052	.052	.052	.053

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	-1.2121	-1.2119	-1.2079	-1.2055	-1.2037	-1.2056	-1.2335	-1.2660
H	11.3000	11.4361	11.4361	14.6131	16.3961	18.4507	24.3569	33.1790

AT TIME T = 2.80024 SECONDS, AFTER 1509 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.0640	.1280	.1920	.2560	.3200	.3840	.4479	.5119	.5759	.6399	.7039	.7679	.8319	.8959
LOC.	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
U	.000	-.072	-.144	-.217	-.289	-.363	-.437	-.509	-.579	-.643	-.700	-.746	-.781	-.805	-.820
Z	.045	.045	.045	.045	.045	.045	.046	.046	.047	.048	.048	.049	.050	.050	.051

DIST.	.9599	1.0239	1.0879	1.1519
LOC.	15	16	17	18
U	-.826	-.827	-.824	-.818
Z	.051	.052	.052	.052

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	-1.2115	-1.2115	-1.2074	-1.2069	-1.2072	-1.2341	-1.2745	-1.2819
H	11.3000	11.3880	11.3880	14.2556	16.5336	22.5453	30.2957	33.1790

AT TIME T = 2.81879 SECONDS, AFTER 1519 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.0640	.1280	.1920	.2560	.3200	.3840	.4479	.5119	.5759	.6399	.7039	.7679	.8319	.8959
LOC.	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
U	.000	-.074	-.148	-.223	-.297	-.373	-.449	-.523	-.594	-.657	-.712	-.755	-.787	-.809	-.821
Z	.045	.045	.046	.046	.046	.046	.047	.047	.048	.049	.049	.050	.050	.051	.051

DIST.	.9599	1.0239	1.0879	1.1519
LOC.	15	16	17	18
U	-.827	-.827	-.823	-.816
Z	.051	.052	.052	.052

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	-1.2104	-1.2104	-1.2063	-1.2090	-1.2371	-1.2756	-1.2823	-1.2824
H	11.3000	11.3939	11.3939	14.5853	20.3851	28.3368	31.3833	33.1790

AT TIME T = 2.83735 SECONDS, AFTER 1529 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.0640	.1280	.1920	.2560	.3200	.3840	.4479	.5119	.5759	.6399	.7039	.7679	.8319	.8959
LOC.	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
U	.000	-.076	-.152	-.229	-.306	-.384	-.462	-.537	-.608	-.670	-.722	-.763	-.792	-.811	-.822
Z	.046	.046	.046	.047	.047	.047	.048	.048	.049	.049	.050	.050	.051	.051	.051

DIST.	.9599	1.0239	1.0879
LOC.	15	16	17
U	-.826	-.825	-.820
Z	.051	.052	.052

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	-1.2129	-1.2135	-1.2094	-1.2364	-1.2774	-1.2852	-1.2837	-1.2828
H	11.3000	11.5704	11.5704	18.7790	26.3465	29.1987	31.2601	33.1790

AT TIME T = 2.85591 SECONDS, AFTER 1539 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.0640	.1280	.1920	.2560	.3200	.3840	.4479	.5119	.5759	.6399	.7039	.7679	.8319	.8959
LOC.	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
U	.000	-.078	-.157	-.236	-.315	-.395	-.475	-.551	-.621	-.682	-.731	-.769	-.795	-.813	-.822
Z	.047	.047	.047	.047	.048	.048	.049	.049	.050	.050	.050	.051	.051	.051	.051

DIST.	.9599	1.0239
LOC.	15	16
U	-.825	-.823
Z	.051	.052

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	-1.2604	-1.2618	-1.2576	-1.2775	-1.2842	-1.2852	-1.2856	-1.2850
H	11.3000	12.6650	12.6650	24.5675	27.5657	29.2671	31.0381	33.1790

AT TIME T = 2.87447 SECONDS, AFTER 1549 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.0640	.1280	.1920	.2560	.3200	.3840	.4479	.5119	.5759	.6399	.7039	.7679	.8319	.8959
LOC.	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14

U	.000	-.081	-.162	-.243	-.325	-.407	-.488	-.564	-.633	-.691	-.738	-.773	-.797	-.813	-.821
Z	.048	.048	.048	.048	.049	.049	.050	.050	.050	.051	.051	.051	.051	.051	.051

DIST.	.9599	1.0239
LOC.	15	16
U	-.823	-.820
Z	.051	.052

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	-1.3466	-1.3448	-1.3403	-1.3051	-1.2853	-1.2847	-1.2865	-1.2884
H	11.3000	12.2553	12.2553	22.7221	27.4856	29.4040	31.2278	33.1790

AT TIME T = 2.89302 SECONDS, AFTER 1559 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.0640	.1280	.1920	.2560	.3200	.3840	.4479	.5119	.5759	.6399	.7039	.7679	.8319	.8959
LOC.	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
U	.000	-.083	-.167	-.251	-.336	-.419	-.501	-.576	-.643	-.699	-.743	-.775	-.798	-.812	-.819
Z	.049	.049	.049	.049	.050	.050	.051	.051	.051	.051	.051	.051	.051	.051	.051

DIST.	.9599	
LOC.	15	
U	-.820	
Z	.051	

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	-1.3652	-1.3650	-1.3604	-1.3478	-1.3054	-1.2865	-1.2874	-1.2879
H	11.3000	11.4732	11.4732	16.4923	24.5791	29.4463	31.5843	33.1790

AT TIME T = 2.91158 SECONDS, AFTER 1569 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.0640	.1280	.1920	.2560	.3200	.3840	.4479	.5119	.5759	.6399	.7039	.7679	.8319	.8959
LOC.	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
U	.000	-.086	-.173	-.260	-.346	-.432	-.513	-.587	-.651	-.704	-.746	-.776	-.797	-.810	-.816
Z	.050	.050	.050	.050	.051	.051	.052	.052	.052	.052	.052	.052	.052	.051	.051

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	-1.3655	-1.3655	-1.3609	-1.3605	-1.3487	-1.3080	-1.2880	-1.2865
H	11.3000	11.4255	11.4255	14.6376	18.4959	26.7764	31.4396	33.1790

AT TIME T = 2.93014 SECONDS, AFTER 1579 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.0640	.1280	.1920	.2560	.3200	.3840	.4479	.5119	.5759	.6399	.7039	.7679	.8319	.8959
LOC.	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
U	.000	-.090	-.179	-.269	-.357	-.443	-.524	-.596	-.658	-.708	-.747	-.776	-.796	-.808	-.813
Z	.051	.051	.051	.052	.052	.052	.053	.053	.053	.052	.052	.052	.052	.052	.051

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	-1.3655	-1.3655	-1.3609	-1.3618	-1.3629	-1.3499	-1.3070	-1.2880
H	11.3000	11.4372	11.4372	14.7094	16.8631	20.5323	28.4325	33.1790

AT TIME T = 2.94869 SECONDS, AFTER 1589 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.0640	.1280	.1920	.2560	.3200	.3840	.4479	.5119	.5759	.6399	.7039	.7679	.8319
LOC.	0	1	2	3	4	5	6	7	8	9	10	11	12	13
U	.000	-.093	-.186	-.278	-.368	-.454	-.533	-.603	-.662	-.710	-.747	-.775	-.793	-.804
Z	.052	.052	.052	.053	.053	.053	.054	.053	.053	.053	.052	.052	.052	.052

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	-1.3670	-1.3671	-1.3624	-1.3633	-1.3629	-1.3617	-1.3496	-1.3272
H	11.3000	11.4694	11.4694	14.9386	16.7486	18.5498	22.3570	33.1790

AT TIME T = 2.96725 SECONDS, AFTER 1599 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.0640	.1280	.1920	.2560	.3200	.3840	.4479	.5119	.5759	.6399	.7039	.7679
LOC.	0	1	2	3	4	5	6	7	8	9	10	11	12
U	.000	-.097	-.193	-.287	-.378	-.464	-.541	-.608	-.665	-.711	-.746	-.772	-.790
Z	.054	.054	.054	.054	.054	.054	.054	.054	.054	.053	.053	.052	.052

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	-1.3702	-1.3701	-1.3655	-1.3636	-1.3620	-1.3627	-1.3816	-1.4107
H	11.3000	11.4652	11.4652	14.7863	16.6261	18.5765	23.3525	33.1790

AT TIME T = 2.98581 SECONDS, AFTER 1609 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.0640	.1280	.1920	.2560	.3200	.3840	.4479	.5119	.5759	.6399	.7039
LOC.	0	1	2	3	4	5	6	7	8	9	10	11
U	.000	-.100	-.200	-.296	-.388	-.472	-.547	-.612	-.666	-.710	-.744	-.769
Z	.055	.055	.055	.055	.056	.056	.055	.055	.054	.054	.053	.052

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	-1.3698	-1.3698	-1.3652	-1.3642	-1.3633	-1.3818	-1.4234	-1.4355
H	11.3000	11.4037	11.4037	14.4329	16.6148	21.4132	29.4021	33.1790

AT TIME T = 3.00436 SECONDS, AFTER 1619 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.0640	.1280	.1920	.2560	.3200	.3840	.4479	.5119	.5759	.6399	.7039

LOC.	0	1	2	3	4	5	6	7	8	9	10	11
U	.000	-.104	-.206	-.304	-.396	-.478	-.551	-.613	-.665	-.707	-.740	-.763
Z	.056	.056	.057	.057	.057	.057	.056	.056	.055	.054	.053	.053

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	-1.3680	-1.3680	-1.3634	-1.3649	-1.3839	-1.4237	-1.4355	-1.4363
H	11.3000	11.4067	11.4067	14.5105	19.2061	27.3993	31.2485	33.1790

AT TIME T = 3.02292 SECONDS, AFTER 1629 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.0640	.1280	.1920	.2560	.3200	.3840	.4479	.5119	.5759	.6399
LOC.	0	1	2	3	4	5	6	7	8	9	10
U	.000	-.107	-.212	-.311	-.402	-.482	-.552	-.612	-.662	-.703	-.734
Z	.058	.058	.058	.058	.058	.058	.057	.056	.055	.054	.053

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	-1.3682	-1.3685	-1.3639	-1.3830	-1.4250	-1.4374	-1.4363	-1.4356
H	11.3000	11.5021	11.5021	17.4414	25.2543	29.0100	31.2125	33.1790

AT TIME T = 3.04148 SECONDS, AFTER 1639 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.0640	.1280	.1920	.2560	.3200	.3840	.4479	.5119	.5759
LOC.	0	1	2	3	4	5	6	7	8	9
U	.000	-.111	-.217	-.317	-.406	-.484	-.551	-.609	-.658	-.696
Z	.060	.060	.060	.059	.059	.059	.058	.057	.056	.055

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	-1.3990	-1.4005	-1.3958	-1.4237	-1.4362	-1.4375	-1.4374	-1.4365
H	11.3000	12.3746	12.3746	23.4820	27.2115	29.0619	30.9842	33.1790

AT TIME T = 3.06003 SECONDS, AFTER 1649 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.0640	.1280	.1920	.2560	.3200	.3840	.4479	.5119
LOC.	0	1	2	3	4	5	6	7	8
U	.000	-.113	-.221	-.320	-.407	-.483	-.549	-.604	-.650
Z	.061	.061	.061	.061	.060	.060	.059	.057	.056

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	-1.4827	-1.4814	-1.4764	-1.4487	-1.4362	-1.4363	-1.4378	-1.4392
H	11.3000	12.4905	12.4905	23.4025	27.2831	29.1846	31.0707	33.1790

AT TIME T = 3.07859 SECONDS, AFTER 1659 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.0640	.1280	.1920	.2560	.3200	.3840	.4479
LOC.	0	1	2	3	4	5	6	7
U	.000	-.114	-.223	-.321	-.406	-.480	-.543	-.596
Z	.063	.063	.063	.062	.062	.060	.059	.058

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	-1.5125	-1.5120	-1.5069	-1.4885	-1.4487	-1.4365	-1.4381	-1.4390
H	11.3000	11.5465	11.5465	17.6046	25.3887	29.2911	31.4192	33.1790

AT TIME T = 3.09715 SECONDS, AFTER 1669 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.0640	.1280	.1920	.2560	.3200
LOC.	0	1	2	3	4	5
U	.000	-.114	-.222	-.318	-.402	-.474
Z	.065	.065	.065	.064	.063	.061

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	-1.5129	-1.5129	-1.5078	-1.5066	-1.4885	-1.4504	-1.4377	-1.4369
H	11.3000	11.4427	11.4427	14.8464	19.6534	27.6347	31.4404	33.1790

AT TIME T = 3.11571 SECONDS, AFTER 1679 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.0640	.1280	.1920
LOC.	0	1	2	3
U	.000	-.112	-.218	-.313
Z	.068	.067	.067	.065

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	-1.5121	-1.5121	-1.5070	-1.5077	-1.5081	-1.4895	-1.4492	-1.4364
H	11.3000	11.4483	11.4483	14.7761	17.1268	21.8428	29.4501	33.1790

THE VAPOR CAVITY HAS COMPLETELY COLLAPSED AT TIME T = 3.13426 SECONDS (OPERATION CYCLE M = 1689). THIS IS 2.93014 SECONDS AFTER COLUMN SEPARATION OCCURRED, AND 3.12870 SECONDS AFTER VALVE WAS CLOSED.

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	-1.5125	-1.5125	-1.5074	-1.5085	-1.5086	-1.5066	-1.4879	-1.4613
H	11.3000	11.4752	11.4752	15.0048	16.9719	18.9788	23.6648	33.1790

AT TIME T = 3.13612 SECONDS, AFTER 1690 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	.0000	-1.5127	-1.5076	-1.5085	-1.5084	-1.5068	-1.4916	-1.4673
H	126.5298	11.4788	11.4788	15.0196	16.9606	18.9115	23.1907	33.1790

AT TIME T = 3.15468 SECONDS, AFTER 1700 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	.0000	-.0919	-.0916	-1.5083	-1.5069	-1.5072	-1.5217	-1.5457
H	222.3961	220.4687	220.4687	14.9212	16.8446	18.8398	23.1672	33.1790

AT TIME T = 3.17323 SECONDS, AFTER 1710 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	.0000	-.0077	-.0077	-.0939	-1.5070	-1.5217	-1.5610	-1.5756
H	233.3888	233.2271	233.2271	222.9844	16.8012	21.0872	28.8351	33.1790

AT TIME T = 3.19179 SECONDS, AFTER 1720 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	.0000	-.0011	-.0011	-.0103	-.1127	-1.5605	-1.5753	-1.5761
H	234.4422	234.4238	234.4238	235.8169	226.6305	26.7563	31.1035	33.1790

AT TIME T = 3.21035 SECONDS, AFTER 1730 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	.0000	-.0017	-.0017	-.0196	-.0676	-.1704	-1.5756	-1.5750
H	234.8549	234.8720	234.8720	239.3619	245.1795	235.9953	31.1333	33.1790

AT TIME T = 3.22890 SECONDS, AFTER 1740 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	.0000	-.0150	-.0150	-.0589	-.0770	-.0868	-.1745	-1.5751
H	237.6604	237.8206	237.8206	245.4985	248.7567	248.9576	237.4697	33.1790

→ THE DIRECTION OF FLOW AT THE RESERVOIR END OF THE PIPE SYSTEM HAS REVERSED AT TIME T = 3.23540 SECONDS. ←

AT TIME T = 3.24746 SECONDS, AFTER 1750 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	.0000	-.0288	-.0287	-.0724	-.0781	-.0808	-.0904	1.2190
H	247.7477	247.7045	247.7045	248.4821	249.2789	250.2749	250.4436	33.1790

AT TIME T = 3.26602 SECONDS, AFTER 1760 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	.0000	-.0104	-.0104	-.0479	-.0762	-.0816	1.3095	1.3883
H	255.5118	255.3711	255.3711	252.7516	249.9986	250.7663	46.5190	33.1790

AT TIME T = 3.28457 SECONDS, AFTER 1770 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	.0000	-.0021	-.0021	-.0143	-.0516	1.3108	1.3936	1.3998
H	257.3105	257.2807	257.2807	258.1508	254.2275	46.7309	34.0492	33.1790

AT TIME T = 3.30313 SECONDS, AFTER 1780 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE

FLOW SYSTEM ARE AS TABULATED BELOW.

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	.0000	-.0012	-.0012	-.0057	1.3692	1.4201	1.4010	1.3989
H	257.8703	257.8616	257.8616	260.0297	55.3635	38.0023	33.4494	33.1790

AT TIME T = 3.32169 SECONDS, AFTER 1790 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	.0000	-.0016	-.0016	1.3787	1.4622	1.4589	1.4252	1.4022
H	258.4284	258.4250	258.4250	56.8706	44.3148	42.0606	37.1541	33.1790

AT TIME T = 3.32540 SECONDS, AFTER 1792 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	.0000	.9842	.9809	1.4153	1.4652	1.4623	1.4330	1.4067
H	211.3071	183.4390	183.4390	51.4954	43.9692	42.5557	38.3408	33.1790

AT TIME T = 3.32725 SECONDS, AFTER 1793 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	.0000	1.1050	1.1013	1.4276	1.4661	1.4635	1.4368	1.4098
H	158.0020	149.7719	149.7719	49.6803	43.8552	42.7476	38.9261	33.1790

AT TIME T = 3.32911 SECONDS, AFTER 1794 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	.0000	1.0954	1.0917	1.4372	1.4669	1.4646	1.4406	1.4138
H	110.1061	111.0738	111.0738	48.2775	43.7719	42.9110	39.4920	33.1790

AT TIME T = 3.33097 SECONDS, AFTER 1795 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	.0000	1.0256	1.0222	1.4445	1.4674	1.4653	1.4442	1.4184
H	67.3567	72.5709	72.5709	47.1905	43.7079	43.0444	40.0207	33.1790

AT TIME T = 3.33282 SECONDS, AFTER 1796 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	.0000	.9293	.9262	1.4502	1.4678	1.4660	1.4477	1.4238
H	29.5638	36.6482	36.6482	46.3516	43.6630	43.1578	40.5059	33.1790

COLUMN SEPARATION HAS OCCURRED AT THE GATE VALVE AT TIME T = 3.33468 SECONDS (OPERATION CYCLE NO. 1797). THIS IS 3.32911 SECONDS AFTER CLOSURE OF THE GATE VALVE.

THE MAGNITUDE OF DELXC REMAINS THE MINIMUM VALUE.

GIVEN DATA AND COMPUTED VALUES PERTINENT TO COMPUTATION OF FLOW FOLLOWING COLUMN SEPARATION.

HVAPOR = 11.3000	DELXC = .0640	DELTC = .00928	MARK = 1689	MUCH = .1450	
FACTOR = 5	XI = .0250	INC = 90	IOTA = .0001	PAREA = .00538	

THE INITIAL VELOCITIES AND DEPTHS IN THE VAPOR CAVITY ARE LISTED BELOW.

DIST.	.0000	.0640
LOC.	0	1
U	.000	.767
Z	.063	.074

THE VELOCITIES AND ABSOLUTE HEADS THROUGHTOUT THE REMAINDER OF THE FULL-FLOWING PIPE SYSTEM ARE AS LISTED BELOW.

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	.7565	.9453	.9421	1.4546	1.4686	1.4664	1.4309	1.4296
H	11.3000	22.2504	22.2504	45.7018	43.6285	43.2483	40.9318	33.1790

AT TIME T = 3.34210 SECONDS, AFTER 1801 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.0640
LOC.	0	1
U	.000	.589
Z	.058	.068

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	.9856	1.0475	1.0440	1.6061	1.4683	1.4672	1.4626	1.4591
H	11.3000	11.3000	11.3000	65.1767	43.5751	43.4822	41.9209	33.1790

AT TIME T = 3.35138 SECONDS, AFTER 1806 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.0640	.1280
LOC.	0	1	2
U	.000	.468	.906
Z	.056	.062	.071

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	1.0693	1.0797	1.0761	1.2425	1.4680	1.4675	1.4777	1.4963
H	11.3000	11.3000	11.3000	11.3000	43.5981	43.5579	41.2864	33.1790

AT TIME T = 3.36066 SECONDS, AFTER 1811 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.0640	.1280
LOC.	0	1	2
U	.000	.400	.791
Z	.053	.058	.066

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	1.1003	1.1181	1.1143	1.2398	1.6081	1.4701	1.4969	1.5276
H	11.3000	11.3000	11.3000	11.3000	64.3438	43.1690	38.9629	33.1790

AT TIME T = 3.36994 SECONDS, AFTER 1816 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS

VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.0640	.1280	.1920
LOC.	0	1	2	3
U	.000	.349	.694	.965
Z	.051	.055	.062	.072

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	1.1277	1.1310	1.1272	1.2327	1.2479	1.4797	1.5158	1.5312
H	11.3000	11.3000	11.3000	11.3000	11.4358	41.7385	36.3003	33.1790

AT TIME T = 3.38849 SECONDS, AFTER 1826 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.0640	.1280	.1920	.2560
LOC.	0	1	2	3	4
U	.000	.276	.555	.799	1.000
Z	.048	.050	.056	.063	.074

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	1.1623	1.1638	1.1599	1.2277	1.2503	1.3299	1.5329	1.5352
H	11.3000	11.3000	11.3000	11.3000	11.3000	11.3000	33.7061	33.1790

AT TIME T = 3.40705 SECONDS, AFTER 1836 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.0640	.1280	.1920	.2560
LOC.	0	1	2	3	4
U	.000	.227	.458	.670	.849
Z	.046	.047	.052	.058	.065

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	1.1873	1.1881	1.1840	1.2268	1.2542	1.3283	1.3836	1.5346
H	11.3000	11.3000	11.3000	11.3000	11.3000	11.3000	11.3000	33.1790

AT TIME T = 3.42561 SECONDS, AFTER 1846 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.0640	.1280	.1920	.2560	.3200
LOC.	0	1	2	3	4	5
U	.000	.191	.385	.570	.741	.951
Z	.044	.045	.049	.054	.060	.065

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)

V	1.2060	1.2063	1.2022	1.2289	1.2579	1.3272	1.3815	1.4471
H	11.3000	11.3000	11.3000	11.3000	11.3000	11.3000	11.3000	33.1790

AT TIME T = 3.44416 SECONDS, AFTER 1856 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.0640	.1280	.1920	.2560	.3200	.3840
LOC.	0	1	2	3	4	5	6
U	.000	.163	.328	.491	.654	.836	.977
Z	.043	.044	.046	.051	.056	.060	.068

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	1.2200	1.2202	1.2161	1.2351	1.2612	1.3265	1.3380	1.2552
H	11.3000	11.3000	11.3000	11.3000	11.3000	11.3000	17.1039	33.1790

AT TIME T = 3.46272 SECONDS, AFTER 1866 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.0640	.1280	.1920	.2560	.3200	.3840	.4479
LOC.	0	1	2	3	4	5	6	7
U	.000	.140	.282	.427	.579	.741	.870	1.096
Z	.041	.042	.045	.048	.053	.057	.063	.068

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	1.2308	1.2310	1.2268	1.2436	1.2641	1.3091	1.2306	1.2293
H	11.3000	11.3000	11.3000	11.5296	11.3000	12.7346	29.4578	33.1790

AT TIME T = 3.48128 SECONDS, AFTER 1876 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.0640	.1280	.1920	.2560	.3200	.3840	.4479	.5119
LOC.	0	1	2	3	4	5	6	7	8
U	.000	.121	.245	.375	.515	.661	.789	.975	1.077
Z	.040	.041	.043	.046	.050	.054	.059	.063	.073

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	1.2395	1.2398	1.2356	1.2511	1.2669	1.1998	1.2007	1.2062
H	11.3000	11.3000	11.3000	11.6535	11.3000	24.7443	28.8404	33.1790

AT TIME T = 3.49983 SECONDS, AFTER 1886 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.0640	.1280	.1920	.2560	.3200	.3840	.4479	.5119
LOC.	0	1	2	3	4	5	6	7	8
U	.000	.106	.215	.332	.460	.593	.718	.875	.971
Z	.039	.040	.042	.045	.048	.051	.056	.059	.065

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	1.2470	1.2474	1.2432	1.2581	1.1826	1.1755	1.1756	1.1724
H	11.3000	11.3000	11.3000	11.7124	22.0072	24.9259	28.5106	33.1790

AT TIME T = 3.51839 SECONDS, AFTER 1896 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.0640	.1280	.1920	.2560	.3200	.3840	.4479	.5119	.5759
LOC.	0	1	2	3	4	5	6	7	8	9
U	.000	.092	.190	.296	.413	.534	.655	.795	.892	1.021
Z	.039	.039	.041	.043	.046	.049	.053	.056	.061	.065

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	1.2540	1.2545	1.2502	1.1896	1.1734	1.1586	1.1475	1.1453
H	11.3000	11.3000	11.3000	22.8171	24.3702	25.7683	29.2960	33.1790

AT TIME T = 3.53695 SECONDS, AFTER 1906 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.0640	.1280	.1920	.2560	.3200	.3840	.4479	.5119	.5759	.6399
LOC.	0	1	2	3	4	5	6	7	8	9	10
U	.000	.081	.169	.265	.372	.484	.600	.725	.822	.941	1.100
Z	.038	.039	.040	.042	.045	.047	.051	.054	.058	.062	.072

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	1.1254	1.1317	1.1278	1.1732	1.1657	1.1454	1.1285	1.1227
H	11.3000	12.2281	12.2281	24.1137	26.5588	28.7198	30.4703	33.1790

AT TIME T = 3.55550 SECONDS, AFTER 1916 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.0640	.1280	.1920	.2560	.3200	.3840	.4479	.5119	.5759	.6399
LOC.	0	1	2	3	4	5	6	7	8	9	10
U	.000	.072	.151	.238	.337	.441	.550	.664	.759	.867	.977
Z	.038	.038	.039	.041	.043	.046	.049	.052	.056	.059	.065

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	1.1010	1.1012	1.0975	1.1043	1.1454	1.1356	1.1207	1.1118
H	11.3000	11.4200	11.4200	17.2708	28.4421	31.2384	32.6376	33.1790

AT TIME T = 3.57406 SECONDS, AFTER 1926 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.0640	.1280	.1920	.2560	.3200	.3840	.4479	.5119	.5759	.6399	.7039

LOC.	0	1	2	3	4	5	6	7	8	9	10	11
U	.000	.064	.135	.216	.306	.402	.505	.616	.734	.862	.887	.893
Z	.037	.037	.038	.040	.042	.044	.047	.050	.054	.057	.062	.067

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	1.0806	1.0804	1.0767	1.0701	1.0746	1.1207	1.1195	1.1187
H	11.3000	11.6098	11.6098	17.0467	21.9698	32.3521	33.9754	33.1795

AT TIME T = 3.59262 SECONDS, AFTER 1936 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.0640	.1280	.1920	.2560	.3200	.3840	.4479	.5119	.5759	.6399	.7039	.7679
LOC.	0	1	2	3	4	5	6	7	8	9	10	11	12
U	.000	.058	.122	.196	.279	.369	.465	.561	.649	.742	.814	.849	.890
Z	.037	.037	.038	.039	.041	.043	.046	.048	.052	.055	.059	.064	.074

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	1.0523	1.0494	1.0458	1.0472	1.0458	1.0562	1.1186	1.1261
H	11.3000	11.6259	11.6259	17.5826	20.9895	24.7340	32.9348	33.1796

AT TIME T = 3.61118 SECONDS, AFTER 1946 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.0640	.1280	.1920	.2560	.3200	.3840	.4479	.5119	.5759	.6399	.7039	.7679
LOC.	0	1	2	3	4	5	6	7	8	9	10	11	12
U	.000	.052	.111	.179	.255	.339	.428	.518	.601	.686	.749	.786	.824
Z	.036	.037	.037	.039	.040	.042	.044	.047	.050	.053	.057	.063	.066

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	1.0219	1.0213	1.0178	1.0216	1.0310	1.0441	1.0655	1.1184
H	11.3000	11.5916	11.5916	17.0528	20.3508	21.6104	24.0208	33.1795

AT TIME T = 3.62973 SECONDS, AFTER 1956 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.0640	.1280	.1920	.2560	.3200	.3840	.4479	.5119	.5759	.6399	.7039	.7679	.8319
LOC.	0	1	2	3	4	5	6	7	8	9	10	11	12	13
U	.000	.047	.101	.163	.234	.312	.395	.478	.557	.634	.689	.730	.781	.965
Z	.036	.036	.037	.038	.039	.041	.043	.046	.048	.051	.056	.061	.064	.068

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	.9986	.9988	.9954	1.0018	1.0201	1.0384	1.0444	1.0655
H	11.3000	11.5046	11.5046	15.6446	17.6866	19.6543	21.9354	33.1795

AT TIME T = 3.64829 SECONDS, AFTER 1966 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.0640	.1280	.1920	.2560	.3200	.3840	.4479	.5119	.5759	.6399	.7039	.7679	.8319	.8959
LOC.	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
U	.000	.043	.092	.150	.216	.288	.365	.442	.516	.586	.650	.678	.740	.846	.938
Z	.036	.036	.036	.037	.039	.040	.042	.044	.047	.050	.054	.059	.062	.065	.069

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	.9885	.9876	.9843	.9939	1.0092	1.0205	.9786	.9765
H	11.3000	11.3625	11.3625	13.4266	14.9679	18.0243	23.8318	33.1790

AT TIME T = 3.66685 SECONDS, AFTER 1976 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.0640	.1280	.1920	.2560	.3200	.3840	.4479	.5119	.5759	.6399	.7039	.7679	.8319	.8959
LOC.	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
U	.000	.040	.085	.138	.199	.266	.338	.409	.478	.540	.585	.630	.697	.779	.863
Z	.035	.036	.036	.037	.038	.040	.041	.043	.046	.049	.053	.057	.060	.063	.068

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	.9882	.9881	.9847	.9933	.9945	.9498	.9469	.9519
H	11.3000	11.3006	11.3006	12.2039	13.7745	24.1265	29.2893	33.1790

AT TIME T = 3.68540 SECONDS, AFTER 1986 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.0640	.1280	.1920	.2560	.3200	.3840	.4479	.5119	.5759	.6399	.7039	.7679	.8319	.8959
LOC.	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
U	.000	.037	.079	.128	.185	.247	.313	.379	.442	.498	.539	.587	.655	.729	.803
Z	.035	.035	.036	.036	.038	.039	.041	.043	.045	.048	.052	.055	.058	.061	.064

DIST.	.9599
LOC.	15
U	.991
Z	.075

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	.9917	.9920	.9886	.9927	.9342	.9212	.9232	.9235
H	11.3000	11.3000	11.3000	13.0802	21.3382	25.0180	28.5210	33.1790

AT TIME T = 3.70396 SECONDS, AFTER 1996 COMPLETE CYCLES OF OPERATION, THE VELOCITIES AND DEPTHS IN THE VAPOR CAVITY AS WELL AS VELOCITIES AND PRESSURES AT KEY POINTS THROUGHOUT THE FLOW SYSTEM ARE AS TABULATED BELOW.

VAPOR CAVITY

DIST.	.0000	.0640	.1280	.1920	.2560	.3200	.3840	.4479	.5119	.5759	.6399	.7039	.7679	.8319	.8959
LOC.	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
U	.000	.034	.073	.118	.171	.229	.290	.351	.408	.458	.497	.546	.614	.685	.754
Z	.035	.035	.035	.036	.037	.038	.040	.042	.044	.047	.051	.054	.057	.059	.062

DIST. .9599
LOC. 15
U .869
Z .000

FULL-FLOWING PIPE SYSTEM

LOC.	(1,0)	(1,1)	(2,0)	(2,10)	(2,20)	(2,30)	(2,40)	(2,50)
V	.9953	.9946	.9912	.9386	.9196	.9077	.8979	.8947
H	11.3000	11.3484	11.3484	21.4994	24.2930	25.7316	28.9467	33.1790

COMPUTATION HAS BEEN HALTED BY CUTOFF.

**** ALL INPUT DATA HAVE BEEN PROCESSED.
AT LOC 37716

..999358.....999358.....999358.....999358.....999358.....999358.....999358.....999358.....999358.....999358.....999358.....999358...

JOB NO. 999358 TUESDAY, APRIL 07, 1964 2 16 13.5 AM 2 29 56.5 AM

BALTZER, ROBERT A. G413N 014 256 000 NO.3 $

999358BALTZERG413N3040764945735 1359 1333 0 0 0 24 1 $

CARDS PROCESSED 465, LINES PRINTED 2868, PAGES PRINTED 71, CARDS PUNCHED 0

ELAPSED TIME --

COST	TOTAL	PROCESSING	EXECUTION	LOADING
$ 104.	13' 35.7''	0' .7''	13' 20.1''	0' 14.7''

ALL USERS - PLEASE SEE NOTICE ON BULLETIN BOARD ABOUT CHANGE IN CALLING SEQUENCE FOR GLIMAD.

ALSO, PLEASE SEE NEW NOTICE ABOUT THE PROPER FORM OF THE YELLOW AND GREEN ID CARDS.

..999358.....999358.....999358.....999358.....999358.....999358.....999358.....999358.....999358.....999358.....999358...