DOWNSTREAM HYDRAULIC TRANSIENTS IN COMBINED FREE-SURFACE, PRESSURIZED FLOW PIPELINES

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ABSTRACT

DOWNSTREAM HYDRAULIC TRANSIENTS IN COMBINED

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By

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August 2009

The purpose of this research was to evaluate hydraulic transients in a combined free-surface, pressurized flow system with free-surface supercritical flow. This research focused on cases in which hydraulic transients are generated from the movement of a valve in the pressurized region of the system. A numerical model was developed to predict the hydraulic transients and the model was applied to simulate the hydraulic transients in a water transmission pipeline. The numerical model uses the Method of Characteristics for pressurized flow and supercritical, open-channel hydraulics to simulate the free-surface flow. Hydraulic transients in free-surface flow were not modeled as part of this research. Data analysis on hydraulic transient propagation and interaction with the pressurized/free-surface transition are presented.

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CHAPTER 1

INTRODUCTION

Purpose and Objective

The purpose of this research is to evaluate hydraulic transients in a combined free-surface, pressurized flow (CFSPF) system with supercritical flow. CFSPF systems are hydraulic systems in which both pressurized flow and free-surface flow exist in different parts of the system at the same time.

Evaluation of CFSPF systems typically focus on wastewater and storm water collection systems. The cases analyzed are typically flow transitions from free-surface flow to combined free-surface, pressurized flow and finally into fully pressurized flow. These transitions can generate adverse pressure transients that may damage the system and cause rapid venting of air and water. Most of the systems studied to date typically are laid on mild slopes in which the free-surface flow is subcritical. This research focuses on a well-vented, large-diameter, water transmission pipeline with supercritical free-surface flow. The hydraulic transients analyzed are created from valve movement in the pressurized reach.

The objective of this research is to develop a numerical model for analysis of hydraulic transients in a CFSPF pipeline. The numerical model is applied to a steep slope pipeline in which the free-surface flow is supercritical. The research describes how hydraulic transients propagate. The research presents data on the hydraulic transient interaction with the free-surface/pressurized flow transition.

This research can be used for transient analysis in CFSPF pipelines and to help understand and improve analytical techniques for these systems. Proper analysis techniques and information developed can help prevent unsafe operating conditions, damage due to hydraulic transients, and improper design.

Research Methodology

In this study, we developed a mathematical model solved using current numerical techniques. Flow in the pressurized region of the system will be analyzed using the Method of Characteristics (MOC) and the free-surface flow will be analyzed using numerical methods applied to supercritical flow. Hydraulic transients in free-surface flow were not modeled as part of this research. For all cases, it is assumed that the free-surface/pressurized transition does not move far enough to impact the upstream boundary condition. The internal boundary condition, or the interface between free surface and pressurized flow, will move based on hydraulic conditions in the pressurized region.

This research involves several distinct tasks. The tasks performed are:

1. Review the steady state flow relationships as they apply to CFSPF pipelines.

2. Review the concepts of hydraulic transients and the MOC numerical solution.

3. Develop a numerical model using the MOC with an internal boundary condition that moves based flow conditions in the pipeline.

4. Evaluate the transient concepts of supercritical flow and boundary conditions that apply to supercritical flow. Determine a numerical method to analyze flow in this flow region.

5. Apply the model to simulate a supercritical flow, CFSPF water transmission pipeline. Use the model to predict hydraulic transients generated from movement of a downstream valve in the pressurized region.

6. Analyze and document the propagation of the hydraulic transients.

Thesis Overview

Chapter 2 discusses basic background for the research. The background includes a discussion of CFSPF hydraulics and practical information on CFSPF systems with emphasis on CFSPF systems in water transmission.

Chapter 3 presents a comprehensive review of the literature available on CFSPF systems and focuses on research in two main areas: free-surface to pressurized flow transition studies, and CFSPF system modeling.

Chapter 4 presents the numerical methods that are applied to solve the mathematical model. First, the methods used to calculate the steady state or initial conditions are discussed. Then a numerical method to calculate the hydraulic transients is presented. The presentation includes a review of the governing equations, the MOC, and the appropriate boundary conditions. The numerical method used to calculate the movement of the flow transition internal boundary condition is introduced. Also supercritical, free-surface flow numerical methods are discussed.

In chapter 5, the proposed computer model is described and the computer programming application is documented. The algorithm for the steady state hydraulics program is presented along with a flow chart that summarizes the methodology. Similarly, the routine for the hydraulic transient calculations is discussed with a flow chart showing the algorithm and computer program logic.

Chapter 6 presents results of two case studies that were analyzed using the proposed computer model. In Case 1 a downstream valve is shut and the hydraulic transients created are documented along with the movement of the free-surface/pressurized transition. Five variations in the parameters were introduced to the baseline case to determine the various parameters of the free-surface/pressurized interface. Case 2 involves the opening of a downstream valve. Chapter 7 discusses recommendations for future research and overall conclusions.

CHAPTER 2

BACKGROUND

Most pipelines are designed to flow either free-surface or pressurized. However, there are pipelines that flow pressurized and free-surface simultaneously. The type of flow that exists in these situations is known as combined free-surface, pressurized flow (CFSPF) (Chaudhry 2008).

CFSPF occurs most often in wastewater, stormwater and hydro power systems. In wastewater or stormwater systems, CFSPF can occur when the downstream end of the system becomes pressurized due to a rise in the water surface elevation due to blockage or high flows. At hydroelectric power plants, a tailrace pipeline or tunnel can be designed for free-surface flow. However, under certain conditions the tailrace may become pressurized. This usually occurs after a decrease of flow from the hydroelectric power plant, such as during load rejection.

Combined Free-Surface, Pressurized Flow Pipeline Hydraulics

When flowing at design capacities, the pipeline in a CFSPF system is completely full as shown in Figure 1. Note that upstream flow control is not currently recommended for pipeline design due to operational problems including air entrainment, flow control difficulties, and potential spilling from open vents. Since several water agencies currently own and operate these systems, upstream flow control pipelines are studied for various operational and design modification purposes. At a lower flow, both pressurized and free-surface flow will occur at various reaches in the pipeline as shown in Figure 2.

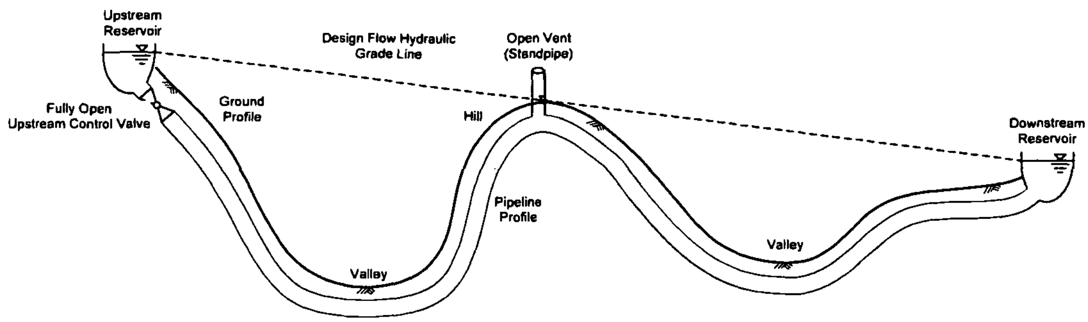


FIGURE 1. Maximum hydrostatic pressure in a CFSPF pipeline.

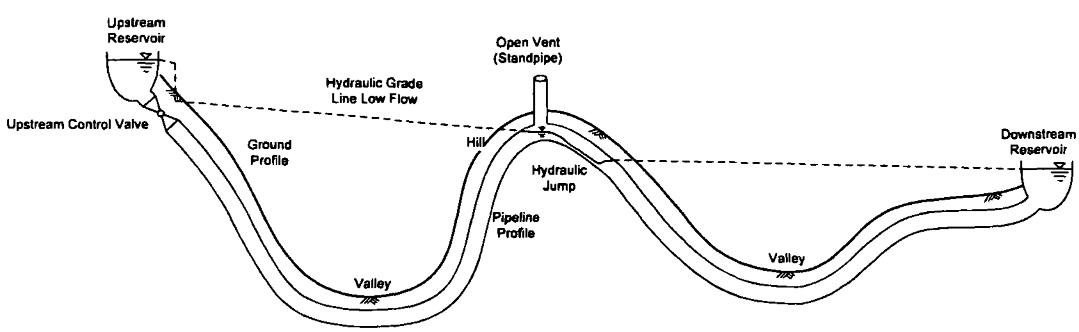


FIGURE 2. CFSPF pipeline at lower flows.

At the downstream reach, the pipeline flows full and a hydraulic jump occurs at the transition between the pressurized and free-surface flow (Sailer 1955) as shown in Figure 3.

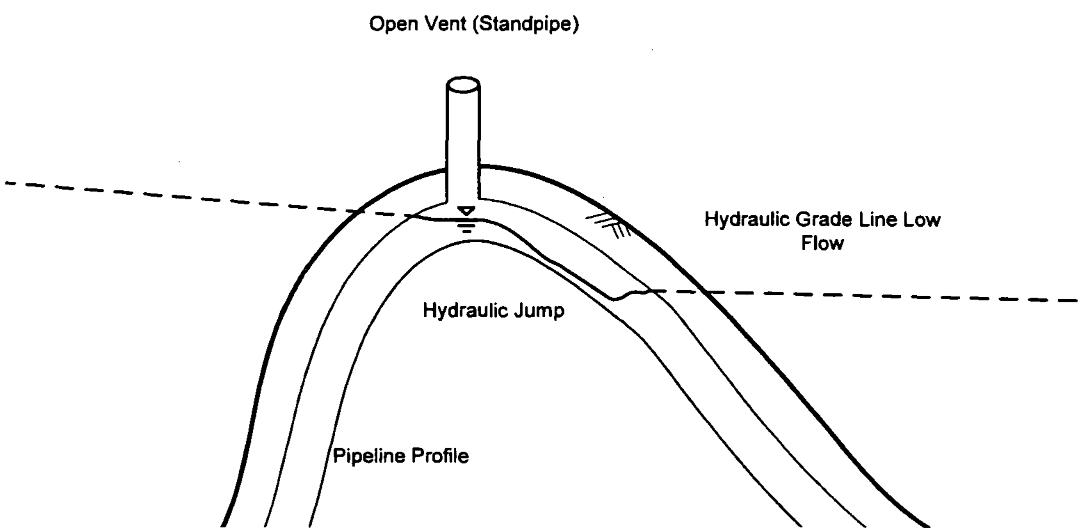


FIGURE 3. Pressurized flow/free-surface flow transition.

The Bernoulli equation, including friction and minor losses, can be used to determine the hydraulic grade line (HGL) for a given flow rate. For the CFSPF pipeline shown in Figure 3, the HGL will intersect the soffit (or the top of the pipe) at the pressurized/free-surface transition. At this location a hydraulic jump will occur (Sailer 1955). This is due to the change from supercritical free-surface flow to a subcritical, pressurized flow regime. The supercritical flow is governed by free-surface flow equations.

Hydraulic transients in CFSPF pipelines can develop by two main methods:

1. Hydraulic transients can form when the flow regime changes rapidly from free-surface/pressurized to fully pressurized.

2. Hydraulic transients can be generated from rapid flow changes in the pressurized flow reach. For example, the rapid closing or opening of a valve, rapid stopping or starting of a pump, or a hydroelectric power plant load acceptance/rejection. These events may occur in the main pipeline or in a branching pipeline.

Water Transmission Pipelines

This research will analyze CFSPF in a water transmission pipeline. The pipeline will be referred to as a CFSPF pipeline and has a control valve near the upstream reservoir to control flow into the pipe. The pipeline is long, has a large-diameter, and is located in hilly terrain. The pipeline is well-vented, meaning air can freely flow in and out of the pipeline at certain high points in the profile.

Upstream controlled, large-diameter water transmission pipelines are not current design practice. However, the United State Bureau of Reclamation, the Metropolitan Water District of Southern California, and the San Diego County Water Authority designed, constructed, and currently operate several CFSPF, upstream controlled, water transmission pipelines. Examples include the Main Aqueduct of the Canadian River Pipeline (Holley 1967), the Coachella Pipeline System (Cassidy 1972), the Upper Feeder, the Lower Feeder, the Palos Verdes Feeder (Whitsett 1969), the First San Diego Aqueduct (Sailer 1955), San Diego Pipeline 3, and San Diego Pipeline 4.

At topographical high points, such as hilltops, air vents allow air to freely enter the pipeline. Some CFSPF pipelines are located along flat topography that gently slopes downward. Check structures can be designed to artificially create topographical high points that vent to atmosphere. These structures should be designed using physical models due to the significant potential for air entrainment in the flow that could lead to violent venting of air from the pipeline. Additional information on air entrainment issues within these pipelines are presented in chapter 3. The check structures also allow water to spill to prevent high pressures in cases where the downstream valve is accidently shut or the flow is blocked. Note that provisions must be made for spillage of water from the check structure and possible de-chlorination in potable water systems. The pipeline can be designed for lower maximum pressure compared to pipelines without check structures. In addition, under low flow conditions the air vent allows air to freely enter into the pipeline when free-surface flow develops as shown in Figure 4.

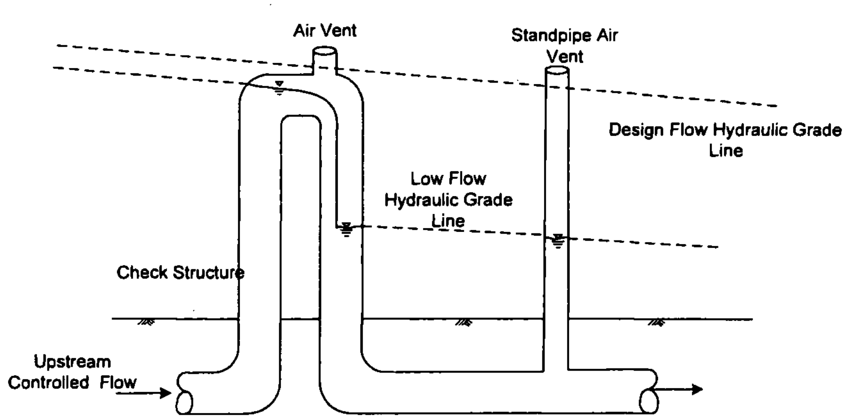


FIGURE 4. CFSPF pipeline typical check structure.

CFSPF pipelines may offer economic benefits as, for example, lower pressure class piping may be installed. This is because the maximum hydraulic grade line will slope down to the downstream reservoir. The pipeline in the downstream reaches of a CFSPF pipeline can have a lower pressure class compared to Figure 5 where it is possible the entire pipeline is subjected to the hydrostatic pressures (or head) of the upstream reservoir.

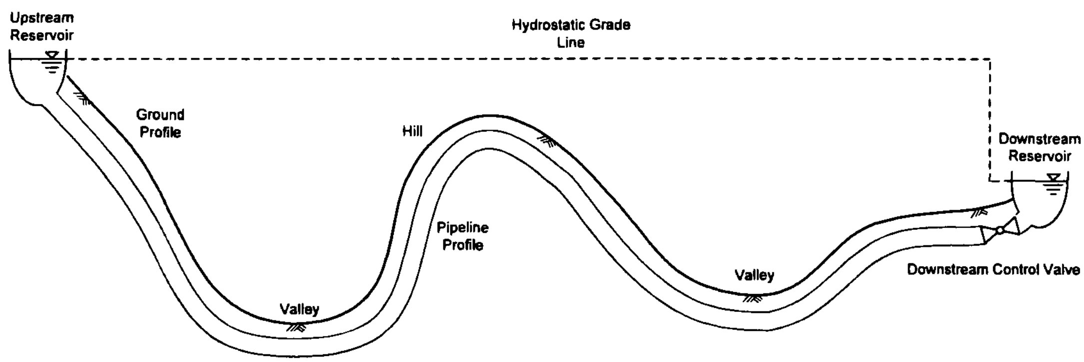


FIGURE 5. Hydrostatic head in pressurized, downstream controlled pipeline.

The reduced hydrostatic pressure will result in a reduced pipe wall thickness and therefore less material costs (Colgate 1967). In pipelines that are very long (tens to hundreds of miles) the material savings may be significant. However, the cost of vent structures, containment of spillage and possible de-chlorination facilities may significantly increase the cost of CFSPF pipelines. Also as discussed previously, CFSPF pipelines may have operational problems including air entrainment and flow control difficulties. The complex flow control may lead to significant loss of water and air entrainment may lead inefficiencies and increased costs during the water filtration process. These potential costs should be considered when designing a CFSPF system.

CHAPTER 3

LITERATURE REVIEW

Literature for CFSPF pipelines focuses on three main subjects: air entrainment, hydraulic transients developed during the transition from fully free-surface flow to fully pressurized flow, and hydraulic transients.

Air Entrainment Literature

Although this current research does not focus on air entrainment, the literature available on air entrainment highlights concepts of CFSPF pipelines.

In 1938, Lane and Kindsvater published a research on the hydraulic jump at the free-surface to pressurized flow interface in circular conduits. They applied the Momentum Equations to mathematically evaluate the hydraulic jump. Kalinkske (1943) verified experimentally the work of Lane and Kindsvater's. He also applied the Momentum Equations to hydraulic jumps in circular conduits with various slopes.

Sailer (1955) documented CFSPF steady state hydraulics. He noted that under low flow conditions a hydraulic jump occurs at the inlet leg of a siphon. Upstream of the hydraulic jump, free-surface flow occurs and downstream of the hydraulic jump, pressurized flow occurs. Whitsett and Christiansen (1969) inspected inside a drained pipeline and visually verified the hydraulics of CFSPF pipelines. They found that in areas where free-surface flow occurred, the invert of the pipeline was scoured clean. In areas were the theory predicted a hydraulic jump, the pipeline interior surface was uniformly clean. The turbulent flow of the hydraulic jump scoured the interior surface of the pipeline. Finally, in areas of pressurized flow they observed that the pipeline interior surfaces were coated with a uniform layer of slime and algae due to the lower velocities.

Flow Transition Literature

Literature on hydraulic transients developed during the transition of flow regimes is mainly of interest in storm water and wastewater applications. However, some concepts also apply to the type of CFSPF pipelines analyzed in this study.

Wiggert (1972) developed a numerical method for analyzing combined free-surface, pressurized systems which he experimentally verified. The analysis focused on a tunnel that transitioned from fully free-surface flow to pressurized flow due to upstream changes. The author developed a mathematical description of the moving free-surface/pressurized boundary. Wiggert used the MOC and an internal boundary to describe the transients as a result of the flow transition.

Advanced mathematics and state of the art research in the area of flow transition is currently being conducted. Recently, Vasconcelos et al. (2006) developed a numerical method to analyze transient conditions in a system transitioning from free-surface to pressurized flow. The numerical method was a variation on the shock-capturing technique and good agreement was observed between the model predictions and experimental results.

Combined Free-Surface, Pressurized Flow System Literature

The final literature category focuses on numerical modeling techniques applied to the overall analysis of CFSPF systems compared to studying just the flow transitions in specific areas of the system.

Caves (1980) developed a set of transient flow equations capable of simulating CFSPF systems. In a later work, Caves (1984) applied the analytical technique to capture the movement of the free-surface and pressurized boundary in CFSPF pipelines. He focused on upstream flow changes and analyzed the hydraulics during pipeline filling. Recently, Fuamba (2002) developed three fully dynamic and transient modeling techniques to predict hydraulic transients in CFSPF systems. Later Fuamba (2007) successfully coupled the MOC for pressurized flow with the MacCormack numerical scheme to create a fully dynamic model for CFSPF pipelines.

CHAPTER 4

NUMERICAL METHODS

The mathematical computer model developed for this research is based on established equations and numerical methods. The governing equations have been solved using a numerical technique that has been implemented in a computer program. The computer program is an algorithm to describe the steady state and transient phenomenon of water flow in a transmission pipeline. This chapter presents the governing equations and the numerical scheme used to solve them. The Nomenclature used in this research is in Table 1.

Mathematical Model

Steady State/Initial Conditions

A steady state hydraulic algorithm was developed to calculate the initial conditions for input into the hydraulic transient model. The steady state program was set up to calculate flow based on three flow conditions: pressurized flow, free-surface flow and flow in the hydraulic jump region.

Pressurized flow conditions are calculated using the energy equation also known as the Bernoulli equation. The equation between sections 1 and 2 in a pipeline, can be written as:

$$\frac{P_1}{\gamma} + z_1 + \frac{V_1^2}{2g} = \frac{P_2}{\gamma} + z_2 + \frac{V_2^2}{2g} + H_L \qquad (4\text{-}1)$$

TABLE 1. Nomenclature

Symbol	Parameter	Symbol	Parameter
A	Area	L	Pipe length
a	Wave Speed	n	Manning's friction factor
B	Hydraulic depth	P	Pressure
c	Celerity, wave speed in free-surface flow	Q	Flow rate
C_v	Flow coefficient	S_f	Slope of friction
D,d	Diameter or Hydraulic depth	S_o	Slope of pipe
dt	Time step	t	Time
dx	Incremental length	t_c	Time of closure
e	Pipe wall thickness	V	Velocity
E	Young's modulus of elasticity	W	Control surface velocity
F	Force	x	linear dimension
f	Friction factor	y_x	Linear dimension, water depth at section x
Fr	Froude Number = $V/\sqrt{gD}$	z, Z	Elevation
g	Acceleration of gravity	ΔP	Pressure difference
H	Piezometric head	ρ	Fluid density
h_f	Headloss due to friction	θ	Angular position
HGL	Hydraulic grade line	ψ	Non-dimensional parameter of the pipe
H_L	Headloss	γ	Specific weight

TABLE 1. Continued

Symbol	Parameter	Symbol	Parameter
K	Bulk modulus	τ	Dimensionless number describing the discharge coefficient times the area of opening of a valve
R	Friction coefficient	τ_o	Surface friction

The terms in the equation are referred to as pressure head (*P/γ*), the elevation head (*z*) and the velocity head ($V^2/2g$) and H_L is the headloss. Equation 4-1 demonstrates that energy in the pipeline decreases in the direction of the flow due to energy lost to friction or other minor losses in the pipeline (such as bends, entrance/exit losses, or valves). In this study, only losses from friction and valves are considered.

The transition between free-surface, supercritical flow and pressurized flow and is represented as a hydraulic jump (Sailer 1955) in the steady state subroutine of the computer program. However, in the transient portion of the program, the hydraulic jump is treated as a variable head reservoir because the pressure upstream of the jump is atmospheric in a well-vented pipeline. For the transient simulation, this representation was considered an appropriate (E. Wylie, personal communication, March 19, 2009). The hydraulic jump parameters are calculated by determining the sequent depth (the water depth or pressure head at the downstream side of the jump) using the following equation (Chow 1959):

$$\frac{y_2}{y_1} = \frac{1}{2}\left(\sqrt{1 + 8Fr_1^{\,2}} - 1\right) \qquad (4\text{-}2)$$

In equation 4-2, y_1 (the depth at section 1) is assumed to be equal to normal depth and the Froude number can be calculated based on the known parameters. The assumption that y_1 is equal to normal depth is valid because the supercritical, free-surface region has a sufficient length to develop normal depth. The length of the jump can be calculated according to the following equation (adopted from Hager 1992):

$$L = 220 tanh \frac{F_{r1}-1}{22} y_1 cos\theta \qquad (4\text{-}3)$$

Figure 6 shows the relevant parameters calculated for the hydraulic jump.

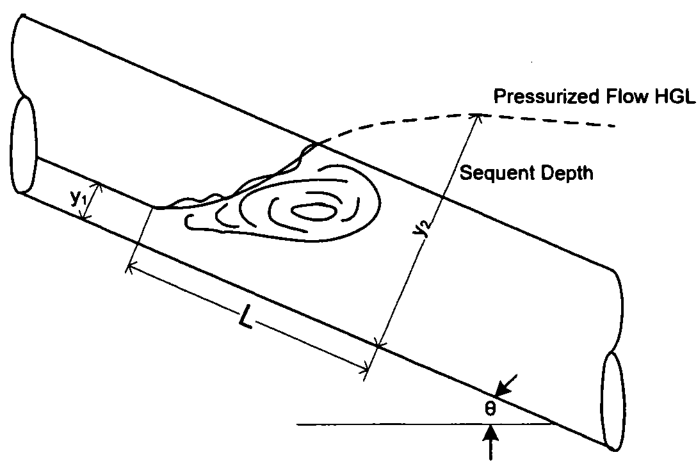


FIGURE 6. Hydraulic jump parameters.

The free-surface water surface profile is calculated using a numerical method for gradually varied flow known as the single-step method (Chaudhry 2008). The single-step method utilized the improved Euler method for improved accuracy. The equation for the improved Euler method for calculation of the water depth, y_{i+1}, based on the depth at the previous location, y_i, is (Chaudhry 2008):

$$y_{i+1} = y_i + \frac{1}{2}[f(x_{i,}y_i) + f(x_{i,}y^*_{i+1})]\Delta x \tag{4-4}$$

where:

$$f(x_{i,}y_i) = \frac{S_o - S_{fi}}{1 - Q^2 B_i/(gA_i^3)} \tag{4-5}$$

where from the Manning's equation,

$$S_f = \frac{n^2 Q^2}{A^2 R^{\frac{4}{3}}} \tag{4-6}$$

and,

$$y^*_{i+1} = y_i + f(x_i, y_i)\Delta x \tag{4-7}$$

so based on the y^*_{i+1} value:

$$f(x_{i,}y^*_{i+1}) = \frac{S_o - S^*_{f\,i+1}}{1 - Q^2 B^*_{i+1}/(gA^{*3}_{i+1})} \tag{4-8}$$

Pressurized Flow Transients

The Method of Characteristics (MOC) was selected as the numerical method to calculate hydraulic transients in the pressurized region of the pipeline. In this section, we will review the governing equations for transient flow conditions, develop the MOC scheme with the boundary conditions and present the numerical algorithm for calculation of the flow, *Q*, and the piezometric head, *H*.

Continuity and momentum equations are used to describe one-dimensional flow in a pressurized conduit.

The continuity equation as applied to the control volume in Figure 7 states that the difference between the mass flow rates into and out of the control volume is equal to the rate of change of mass inside the control volume.

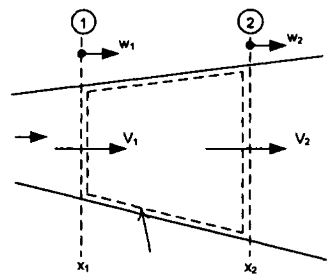


FIGURE 7. Continuity control volume.

Mathematically the continuity equation is (Chaudhry 1987) as follows:

$$\frac{d}{dt}\int_{x_1}^{x_2} \rho A dx + \rho_2 A_2 (V_2 - W_2) - \rho_1 A_1 (V_1 - W_1) = 0 \qquad (4\text{-}9)$$

Where W is the velocity of the control surface (if it is non-stationary) at section 1 for the inflow and at section 2 for the outflow.

Equation 4-9 can be simplified assuming the conduit walls are linearly elastic, as detailed in Chaudhry (1987), to be written as:

$$\frac{\partial p}{\partial t} + V\frac{\partial p}{\partial x} + \rho a^2 \frac{\partial V}{\partial x} = 0 \qquad (4\text{-}10)$$

An important factor in the equation 4-10 is the wave speed, *a*. The wave speed is a characteristic of the conduit and the fluid. It is calculated as follows (Chaudhry 1987):

$$a = \sqrt{\frac{K}{\rho[1+(K/E)\psi]}} \qquad (4\text{-}11)$$

where ψ is a non-dimensional parameter of the pipe representing elastic properties of the pipeline such as pipe joint restraint properties; E is the Young's modulus of elasticity of the conduit walls, K is the bulk modulus of elasticity of the fluid, and ρ is the density of the fluid.

The second equation used to describe one-dimensional, pressurized flow is the momentum equation. The momentum equation states the sum of the forces acting on a control volume is equal to the rate of change of momentum. The momentum equation can be written as (Chaudhry 1987):

$$\frac{d}{dt}\int_{cv} V\rho d\forall + [\rho A(V-W)V]_2 - [\rho A(V-W)V]_1 = \sum F \qquad (4\text{-}12)$$

The various forces acting on the control volume in the direction of flow are shown on Figure 8.

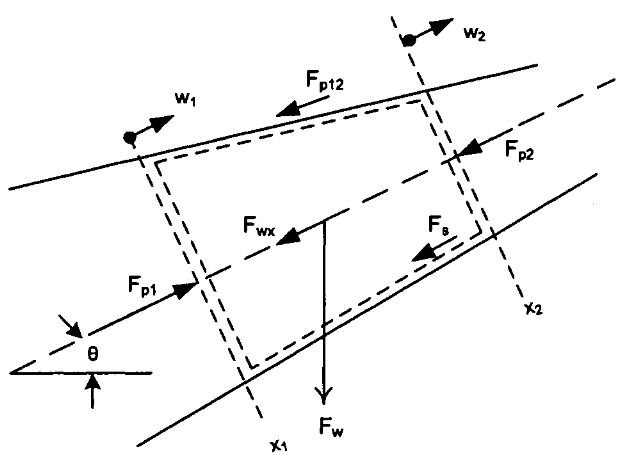


FIGURE 8. Momentum control volume.

The following forces are acting on the control volume:

1. Pressure force acting at section 1 is: $F_{p1} = p_1 A_1$.

2. Pressure force acting at section 2 is: $F_{p2} = p_2 A_2$.

3. The pressure force acting on converging or diverging sides is:

   $F_{p12} = \frac{1}{2}(p_1 + p_2)(A_1 - A_2)$.

4. The weight of the fluid along the centerline of the conduit is:

   $F_{wx} = \rho g A(x_2 - x_1) sin\theta$.

5. The shear force is: $F_s = \tau_o \pi D(x_2 - x_1)$.

The momentum equation can be simplified assuming that headlosses are the same in transient conditions as in steady state conditions as detailed in Chaudhry (1987) to be written as:

$$\frac{\partial V}{\partial t} + V\frac{\partial V}{\partial x} + \frac{1}{\rho}\frac{\partial p}{\partial x} + g sin\theta + \frac{fV|V|}{2D} = 0 \qquad (4\text{-}13)$$

Continuity and momentum equations are used to describe the transient flows in the pressurized flow sections of the pipeline using two independent variables (x and t) and two dependant variables (p and V). The other parameters are system parameters and are assumed not to change with respect to time for the purpose of this study.

Simplifications were made to the momentum and continuity equations for our model. It was assumed that the convective acceleration terms ($V\left(\frac{\partial p}{\partial x}\right)$ and $V\left(\frac{\partial V}{\partial x}\right)$) were small compared to the other terms and could be neglected. In addition, the slope term was neglected because even for the pipeline slopes used in the study the magnitude was small.

The equations were written in terms of piezometric head, *H*, and flow rate, *Q*. After introducing the modifications, the governing equations now become (Chaudhry 1987):

$$\frac{\partial H}{\partial t} + \frac{a^2}{gA}\frac{\partial Q}{\partial x} = 0 \quad (4\text{-}14)$$

$$\frac{\partial Q}{\partial t} + gA\frac{\partial H}{\partial x} + \frac{fQ|Q|}{2DA} = 0 \quad (4\text{-}15)$$

Equations 4-14 and 4-15, represent a system of non-linear, hyperbolic, partial differential equations and can be integrated numerically using the MOC. The MOC is the most accurate and efficient solution of the continuity and momentum equations governing transient flows. The MOC combines the continuity and momentum equations using a linear multiplier as follows (Chaudhry 1987):

$$L = L_1 + \lambda L_2 \quad (4\text{-}16)$$

If $R = f/(2DA)$, then Equations 4-14 and 4-15 become:

$$L_2 = a^2\frac{\partial Q}{\partial x} + gA\frac{\partial H}{\partial t} = 0 \quad (4\text{-}17)$$

$$L_1 = \frac{\partial Q}{\partial t} + gA\frac{\partial H}{\partial x} + RQ|Q| = 0 \quad (4\text{-}18)$$

If $H = H(x,t)$ and $Q = Q(x,t)$, the total derivative is:

$$\frac{dQ}{dt} = \frac{\partial Q}{\partial t} + \frac{\partial Q}{\partial x}\frac{dx}{dt} \quad (4\text{-}19)$$

$$\frac{dH}{dt} = \frac{\partial H}{\partial t} + \frac{\partial H}{\partial x}\frac{dx}{dt} \quad (4\text{-}20)$$

Defining the unknown multiplier, λ, as:

$$\frac{dx}{dt} = \frac{1}{\lambda} = \lambda a^2 \text{ or } \lambda = \pm\frac{1}{a} \quad (4\text{-}21)$$

Equations 4-14 and 4-15 can then converted to ordinary differential equations in the independent variable, *t* (Chaudhry 1987).

$$\frac{dQ}{dt} + \frac{gA}{a}\frac{dH}{dt} + RQ|Q| = 0 \quad (4\text{-}22)$$

if

$$\frac{dx}{dt} = +a \quad (4\text{-}23)$$

and

$$\frac{dQ}{dt} - \frac{gA}{a}\frac{dH}{dt} + RQ|Q| = 0 \quad (4\text{-}24)$$

if

$$\frac{dx}{dt} = -a \quad (4\text{-}25)$$

In Equations 4-23 and 4-25 the velocity is neglected because it is very small compared to the wave speed, *a*. Because of the conversion to ordinary differential equations, the resulting equations are only valid along characteristic lines having slopes of plus or minus *1/a*. Both physically and mathematically, this means that the disturbances will travel along the characteristic lines from points A and B to point P as shown in Figure 9.

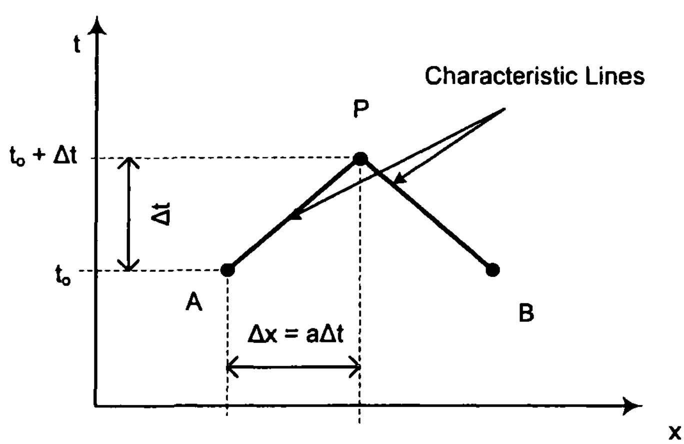


FIGURE 9. Characteristic lines.

Equation 4-22 can then be integrated and multiplied by *dt* to obtain:

$$\int_A^P dQ + \frac{gA}{a}\int_A^P dH + R\int_A^P Q\,|Q|dt = 0 \qquad (4\text{-}26)$$

The term $R\int_A^P Q|Q|dt$ was solved using a first order, linear approximation which assumes Q remains constant from point A to point P (Chaudhry 1987).

$$R\int_A^P Q\,|Q|dt \;\cong RQ_A|Q_A|(t_P - t_A) = \; RQ_A|Q_A|\Delta t \qquad (4\text{-}27)$$

Equations 4-22, 4-23, 4-24, and 4-25 then become:

$$Q_P - Q_A + \frac{gA}{a}(H_P - H_A) + R\Delta t Q_A|Q_A| \qquad (4\text{-}28)$$

and

$$Q_P - Q_B + \frac{gA}{a}(H_P - H_B) + R\Delta t Q_B|Q_B| \qquad (4\text{-}29)$$

Equations for a downstream control valve boundary condition were developed for the pressurized region of the pipeline system. The valve was modeled to discharge to a downstream reservoir with a fixed head. As discussed in chapter 6, the CFSPF pipeline system is usually controlled upstream, however in many cases control valves and isolation valves have been added downstream to CFSPF pipelines for operational and maintenance purposes. The valve boundary condition represents this type of valve.

The downstream boundary condition was described using two factors to account for the headloss through the valve, C_v and τ. The τ factor is used to describe the movement of the valve with respect to time. The initial value of τ can range from 0 to 1.0 in this study. If the control valve is 100-percent open, the value of τ will be 1.0, similarly if the control valve is 50-percent open the value of τ is 0.5 assuming a linear relationship for this example. For various simulations, the value of τ is increased or decreased depending

The value of τ varies in the computer program according to the following equation (Wylie 1993):

$$\tau = \tau_{initial} - \left(\left(\tau_{initial} - \tau_{final} \right) \frac{t}{t_c} \right)^{0.75} \quad (4\text{-}30)$$

where t is the current time in the simulation and t_c is the total time of closure of the valve. The exponential (in this case 0.75) reflects the shape of the τ curve for a specific type of valve as shown in Figure 10.

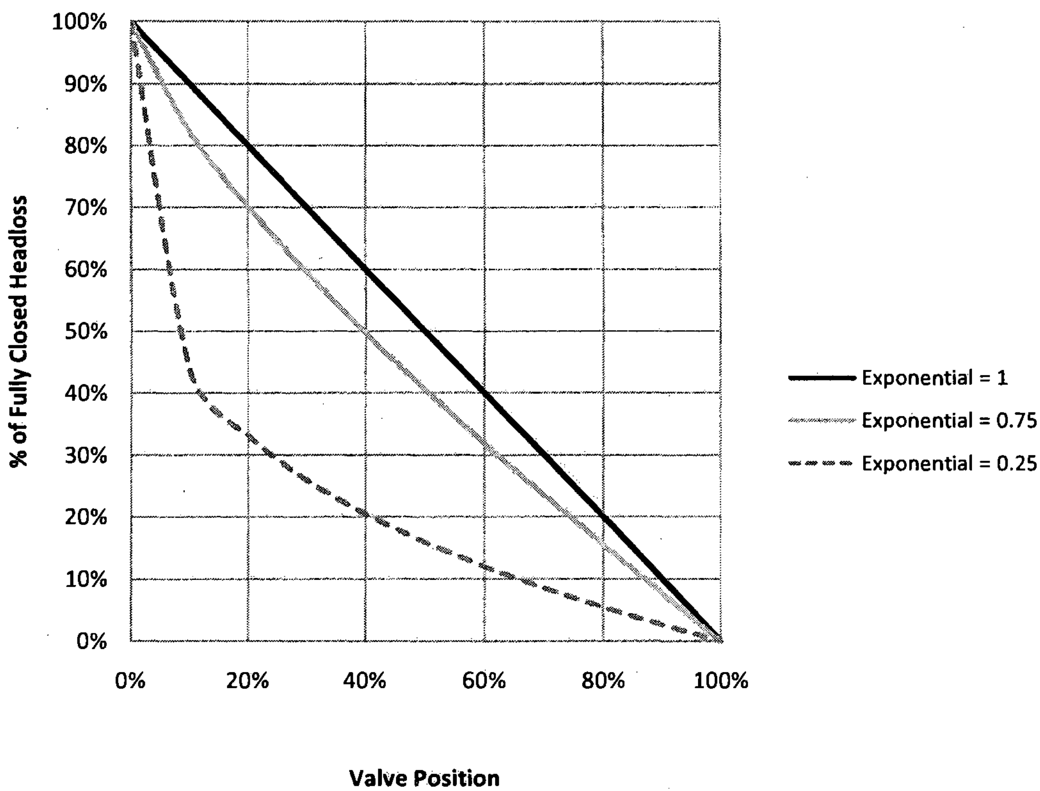


FIGURE 10. Various τ curves.

If the exponential is one, then valve closure headlosses will be linear compared with the valve position. Decreasing values specify a power law curve based on the valve characteristics.

Transition Movement

The transition from free-surface flow to pressurized flow must be calculated separately. The pressurized hydraulic transient equations will not apply to the free-surface flow. For this study, an internal boundary condition was used to separate the free-surface flow from the pressurized flow calculations similar to the one proposed by Wiggert (1972). However the pressurized flow transient equations are not directly coupled to the free-surface flow equations.

The internal boundary condition is initially located near the steady state interface of the free-surface. In most cases, the internal boundary condition cannot be placed at the exact free-surface/pressurized transition because the calculation intervals, *dx*, are not small enough so that a node is placed directly at the actual free-surface/pressurized interface. The internal boundary condition is placed at the nearest node in the pressurized region of flow. It should be noted that the *dx* used in the numerical method were small compared to the length of the pipe (10-feet for a 2000-foot long pipeline). In this author's opinion, this interval spacing is sufficiently fine to capture the movement of the free-surface/pressurized transition for a long pipeline system.

A hydraulic transient in the downstream portion of the pipeline will cause the free-surface/pressurized transition to move. In this study, the movement of a downstream valve generated a hydraulic transient that affects the location of the free-surface/pressurized transition. The water surface elevation directly upstream of the free-surface/pressurized flow transition will increase or decrease. This water surface elevation change is due to the flow change caused by the movement of the valve. The difference can be calculated as the difference in flow coming out of the pipeline compared to flow coming into the pipeline. This increase or decrease can be modeled similar to a surge tank in a system filling or emptying. Using the continuity equation for the system, the flow in the system is

$$Q_S = Q_{us} - Q_{ds} \qquad (4\text{-}31)$$

where Q_s is the filling or emptying flow into the pipeline system, Q_{us} is the flow into the pipeline at the upstream end, Q_{ds} is the flow out of the system at the downstream end (or valve). If:

$$Q_S = A_{transition}\left(\frac{dz}{dt}\right) \qquad (4\text{-}32)$$

where dz is the change in water surface elevation near the free-surface/pressurized transition location and $A_{transition}$ is equal to the area of an ellipse formed by the water surface as shown in Figure 11.

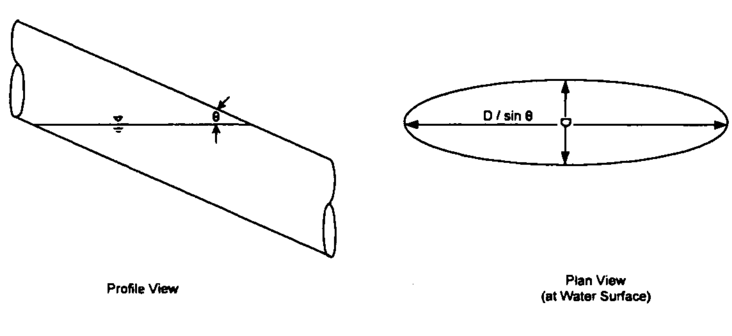


FIGURE 11. Area of transition.

The equation, based on the area of an ellipse is as follows:

$$A_{transition} = \pi ab = \pi \left(\frac{D}{2}\right)(0.5D \frac{1}{Sin\theta}) \quad (4\text{-}33)$$

Equation 4-33 over estimates the area of the transition because it does not account for the free-surface water depth area into the transition and the hydraulic jump is not flat. However, the error introduced by this approximation is sufficiently small. The following equation can be used to determine the increase or decrease in water surface elevation (Chaudhry 1987):

$$\frac{dz}{dt} = \frac{1}{A_{transition}}(Q_{us} - Q_{ds}) \quad (4\text{-}34)$$

It should be noted that this approach neglects the inertia of the fluid at the transition and the pipe wall friction during the movement of the transition.

Free-Surface Flow

In this study we assume that hydraulic transients generated in the downstream, pressurized portion of the pipeline will not impact the supercritical flow in the upstream section of the pipeline. The supercritical flow is controlled upstream. Changes in the water surface elevation and flow can only be caused by upstream changes.

Numerical Schemes

Steady State/Initial Conditions

The pipeline length is discretized into a number of incremental sections, *dx*. The typical notation used for this research and the computer program is shown in Figure 12. The computer program calculates steady state energy from downstream to upstream.

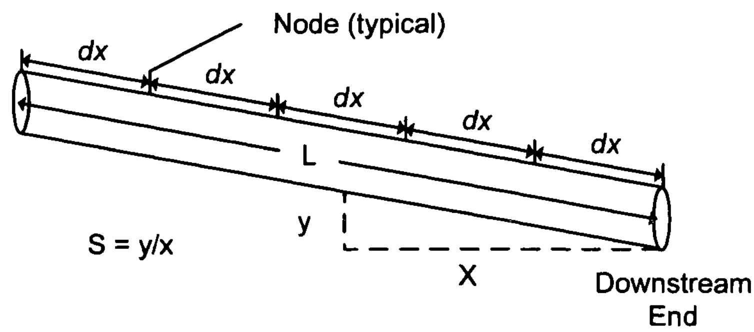


FIGURE 12. Typical notation used in the research.

At each successive node the total energy is equal to the energy at the previous node plus headloss (H_L). The headloss accounts for pipeline friction and valve losses. Friction headlosses for each successive incremental length, *dx*, are calculated based on the Darcy-Weisbach equation for a pressurized pipe. In US Customary units, the equation is written as:

$$H_L = f \frac{L}{D} \frac{V^2}{2g} \tag{4-35}$$

The computer program calculates the steady state hydraulic grade elevation, in terms of feet above mean-sea-level.

For the hydraulic jump, the computer program calculates the depth at each incremental length, *dx*, and reports this information based on an assumed linear (horizontal to the pipe) profile from y_1 to the sequent depth. The depth at each node is calculated by taking the total jump length, *L*, and dividing it by *dx* to get the change in water surface elevation at each length along the hydraulic jump. At each calculated location, or node, along the pipeline the depth y_{i+1} can be calculated based on the depth of water at the previous node.

For free-surface flow, since the flow is supercritical the upstream boundary condition must be used to start the single-step method. When free-surface flow transitions generate from an adverse or horizontal slope, as shown in Figure 13, the depth passes through critical depth and then approaches normal depth (Chow 1959). The critical depth is used as an upstream boundary condition by the program and the single-step method proceeds in a downstream direction, stopping at the hydraulic jump.

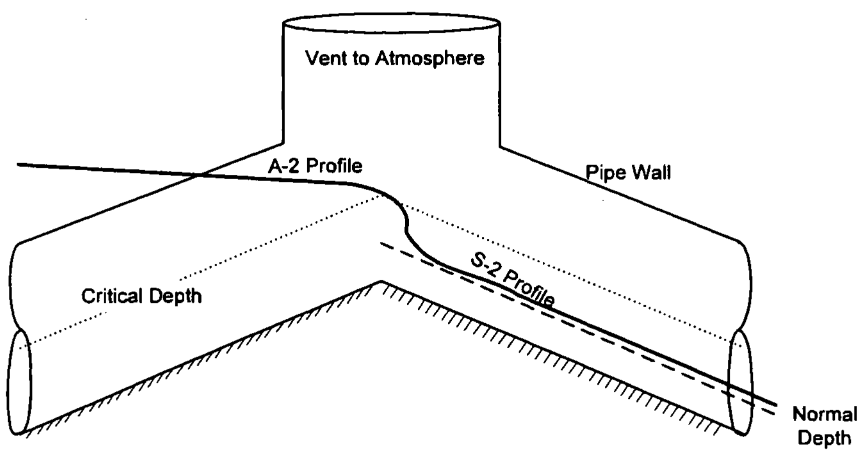


FIGURE 13. Water surface profile upstream end.

The steady state water surface profile or HGL can be calculated along the entire pipeline length based on the type of flow that exists (free-surface, pressurized, and hydraulic jump). A steady hydraulic grade line and water surface profile can be graphically displayed based on the data. The numerical information is used as the initial conditions for the hydraulic transient computations.

Pressurized Flow Transients

A numerical method for solution of Q and H at point P was developed using the following equations:

$$Q_P = 0.5(C_P + C_n) \tag{4-36}$$

where:

$$C_P = Q_A + \frac{gA}{a} H_A - R\Delta t Q_A |Q_A| \tag{4-37}$$

$$C_n = Q_B + \frac{gA}{a} H_B - R\Delta t Q_B |Q_B| \tag{4-38}$$

$$C_a = \frac{gA}{a} \tag{4-39}$$

$$H_P = \frac{Q_P - C_n}{C_a} \tag{4-40}$$

This numerical method can be applied to solve for Q and H at various nodes, or points in the pipeline, and various time steps in the simulation. The numerical scheme requires initial conditions and boundary conditions. To solve for the unknown Q and H at the interior nodes.

To illustrate this procedure Figure 14 shows the characteristic grid which is calculated using this method. As discussed in the "Steady State/Initial Conditions" section, the initial conditions are obtained by using a steady state numerical model and input the solutions into the hydraulic model. The boundary condition calculations are discussed in the "Boundary Conditions" section.

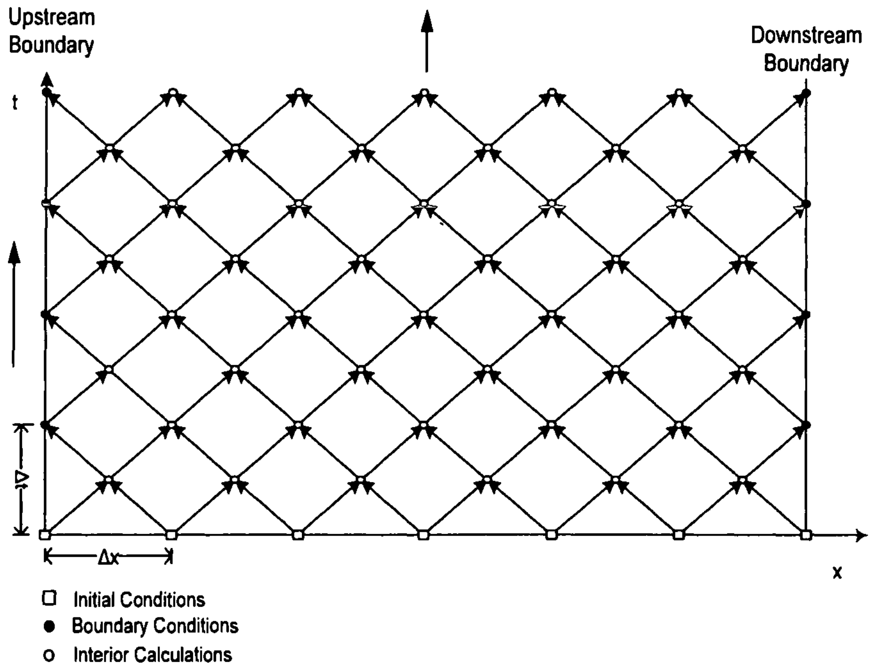


FIGURE 14. Characteristic grid calculation example.

For the valve boundary condition, the numerical model uses the value of τ at each time step to calculate a headloss through the valve for a given flow rate. The equation used is (Wylie 1993):

$$C_V = \tau C_{V\,initial} \tag{4-41}$$

where C_v for water is (Watters 1984):

$$C_V = \frac{Q\ (in\ gpm)}{\sqrt{\Delta P\ (in\ psi)}} \tag{4-42}$$

The Q at the control valve boundary condition can be calculated using the following equation (Chaudhry 1987):

$$Q_P = 0.5\left(-C_V + \sqrt{-C_V^2 + 4C_P C_V}\right) \tag{4-43}$$

and H can be calculated from the following equation (Chaudhry 1987):

$$H_P = \frac{Q_P - C_n}{C_a} \tag{4-44}$$

Using the boundary condition equation 4-44 the value of H and Q can be calculated for each time step in the pressurized flow hydraulic transient simulation so the information at the interior locations can be obtained.

The upstream boundary conditions for the free-surface, supercritical flow used in this study were a fixed water surface elevation and fixed flow. The free-surface flow analyzed in this research was always supercritical. Any disturbances downstream cannot propagate upstream (Akan 2006).

Transition Movement

Movement of the transition upstream is initiated when the HGL elevation downstream of the free-surface/pressurized transition is equal or slightly greater than the sequent downstream depth of the hydraulic jump. When this occurs, the internal boundary condition moves a distance *dx* upstream in the *x* direction. Movement of the transition downstream is initiated when the HGL upstream of the free-surface/pressurized transition is equal or slightly less than the sequent upstream depth of the hydraulic jump. When this occurs, the internal boundary condition moves a distance *dx* downstream in the *x* direction.

The H at the transition is based on the H at the previous timestep plus any increase or decrease in head due to the system filling or emptying. The equation used to describe this is:

$$H_p = H_{p\ at\ i-1} + dz \tag{4-45}$$

The internal boundary condition will allow water to pass in or out of the boundary similarly to a reservoir, so the Q for the internal boundary condition is solved using H_p from the previous calculation:

$$Q_P = C_n + C_a H_P \tag{4-46}$$

Free-Surface Flow

The numerical model developed in this study uses only the steady state conditions to simulate the free-surface flow and water surface elevation. During the simulations, there are no changes in the upstream, free-surface boundary conditions. The only way the upstream boundary condition can be impacted is if the hydraulic jump moves upstream far enough to impact the depth at the upstream boundary.

In the initial stages of the study, a diffusive numerical method presented by Lax in 1954 (Chaudhry 2008) was used to simulate transients in the free-surface portion of the system. This method was found to be unstable in supercritical flow regimes. In addition, large truncation errors were observed. For this research, the effort to couple free-surface transient equations was abandoned in favor of the current method. Numerical methods capable of simulating transients in supercritical flow could be developed and coupled with the current model. This will be discussed further in the "Conclusions" chapter.

CHAPTER 5

COMPUTER PROGRAM

In this chapter, the computer program developed is described. The computer programming application and code is discussed along with the algorithm for both the steady state hydraulics and transient hydraulic conditions.

The computer programming application used to develop this program was Microsoft Visual Basic for Applications (VBA) in conjunction with Microsoft Office Excel 2007 (Excel). VBA is an event driven programming language, meaning the flow of the program is driven by certain events. VBA is used in conjunction with Excel to control various aspects of the Excel application. For this research, VBA was used to read and write data to various cells in the spreadsheet and perform calculations based on the data stored. Various programming loops were written so that the program would perform a certain function until a given criteria was met.

VBA allows the user to interface with the data and determine exact values during each step. The exact calculations and actions of the program can be monitored at each time step using visual debugging functions embedded in VBA and the data input and output can be seen in an Excel spreadsheet.

Recent developments with Microsoft Excel have provided the functionality of additional rows and columns in a spreadsheet. The previous version (Microsoft Office

Excel 2003) was limited to 65,536 rows and 256 columns. Microsoft Office Excel 2007 now allows worksheets sizes up to 1,048,576 rows and 16,384 columns. The larger worksheet size allowed for storage and output of more data and finer meshes to be used.

Steady State Hydraulics

There are three major components to the steady state hydraulic program: the pressurized flow calculations, the hydraulic jump calculations and the free-surface calculations. These three components work as part of an overall program to calculate the hydraulic grade line (HGL) in the pressurized section and the water surface elevation or water surface profile (WSP) in the free-surface and hydraulic jump sections. The program reads the user inputs from given Excel spreadsheet locations and then performs the following tasks:

1. The program calculates the profile of the pipeline on different rows.
2. The program calculates the hydraulic conditions of the pipeline on different rows.

The user inputs for the steady state hydraulics are shown in Table 2. Initial values of variables are calculated based on simple references in the Excel spreadsheet. The variables listed in Table 3 are calculated from user inputs.

The steady state program contains six separate subroutines to calculate the hydraulic parameters: a pipeline profile subroutine, a HGL and WSP subroutine, a normal depth calculator subroutine, a critical depth calculator subroutine, a subroutine to convert SI inputs to US Customary units, and a subroutine to export the steady state results as initial conditions to the hydraulic transient program. The pipeline profile subroutine uses the pipeline slope, length, and number of computation steps to calculate the pipeline profile.

TABLE 2. User Inputs for Steady State Hydraulics Program

User Input	Symbol	Units
Pipe Diameter	D	inches
Pipeline Length	L	feet
Pipeline Slope	S	feet/feet
Flow	Q	cubic-feet per second
Manning's n (Free-Surface)	n	-
Darcy Weisbach Friction Factor (Pressurized Flow)	f	-
Downstream HGL (upstream of valve)	-	feet
Number of computations (or number of calculation lengths)	N	-

TABLE 3. Excel Calculated Steady State Values for Program Input

Excel Calculated Information	Symbol	Units
Pressurized Area	A_p	square feet
Pressurized Velocity	V_p	feet per second
Pressurized Conduit Froude Number	Fr_p	-
Sequent depth	y_1	feet
Free-Surface Area	A_{fs}	square feet
Free-Surface Velocity	V_{fs}	feet per second
Free-Surface Froude Number	Fr_{fs}	-
Hydraulic Jump Length	l	feet

The pipeline profile consists of the length, the invert elevations and the top of pipe elevations for the pipeline.

The normal depth subroutine calculates the normal depth for a given slope, Manning friction factor, flow and diameter. The subroutine starts with an assumed normal depth and changes the depth until the following equation converges with a +/- 0.01-feet tolerance (Chow 1959).

$$f(y_n) = AR^{\frac{2}{3}} - \frac{nQ}{1.49\sqrt{S}} \tag{5-1}$$

The critical depth calculation subroutine is similar to the normal depth calculation subroutine. Based on a given pipeline slope, diameter and flow, a certain critical depth is assumed. The subroutine calculates the critical depth starting with an assumed depth using the function for critical depth until the following equation converges with a +/- 0.01-feet tolerance (Chow 1959).

$$f(Z) = A\sqrt{D} - \frac{Q\sqrt{\cos S}}{\sqrt{g}} \tag{5-2}$$

The metric input subroutine simply converts a set of user input data from SI units to US Customary units. This subroutine was useful for comparing results with data published in metric units and allows users to do work in both unit systems.

The steady state subroutine calculates the HGL and WSP. There are three separate loops within the subroutine; one calculates the pressurized flow HGL, the second calculates the WSP across the hydraulic jump location, and the third calculates the free-surface flow WSP. Figure 15 shows a flow diagram for both the pipeline profile subroutine, which feeds into the HGL and WSP subroutine.

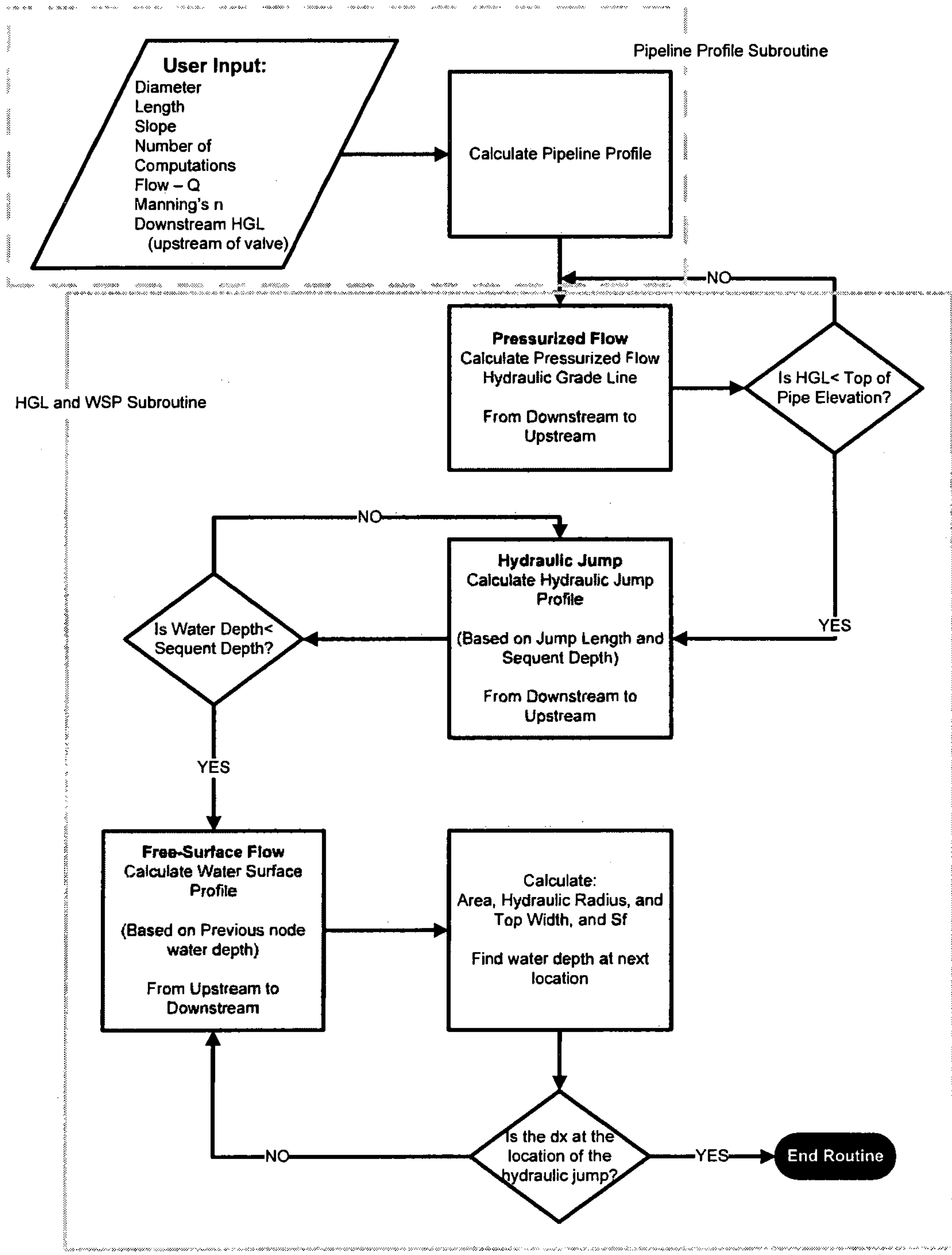


FIGURE 15. Steady state program flow chart.

The pressurized flow loop calculates the HGL at each point along the pipeline until the HGL is equal to or less than the sequent depth of the hydraulic jump. Then the hydraulic jump loop calculates the WSP in the hydraulic jump assuming the profile connects the sequent depth with the initial water depth. When the calculated depth in the hydraulic jump is less than the sequent depth, or depth at the upstream end of the hydraulic jump, the loop is terminated. Finally, the free-surface WSP is calculated based on the starting critical depth at the upstream end of the pipeline. The water depth is then calculated from upstream to downstream. This loop ends when the calculation reaches the hydraulic jump location. At each step in the subroutine, the information for the pipeline profile and the HGL/WSP is output into spreadsheet cells. The cells form an output table on an Excel worksheet showing the x location, the pipeline invert, the top of pipe elevation, the HGL or WSP, the water depth (when the flow is free-surface flow), and the velocity at each location. From this information, a steady state hydraulic profile can be graphed. An example of this graph is shown in Figure 16. This information helps the user to visually determine the steady state hydraulic conditions. The steady state program user interface for the Excel application is shown in Appendix A. It is important to note that the downstream HGL value represents the HGL on the upstream side of the control valve. The program assumes the valve discharges to a fixed head reservoir at a user specified elevation above mean sea level. If a downstream reservoir is selected as the downstream boundary condition, then the downstream HGL represents the water surface elevation at the downstream reservoir.

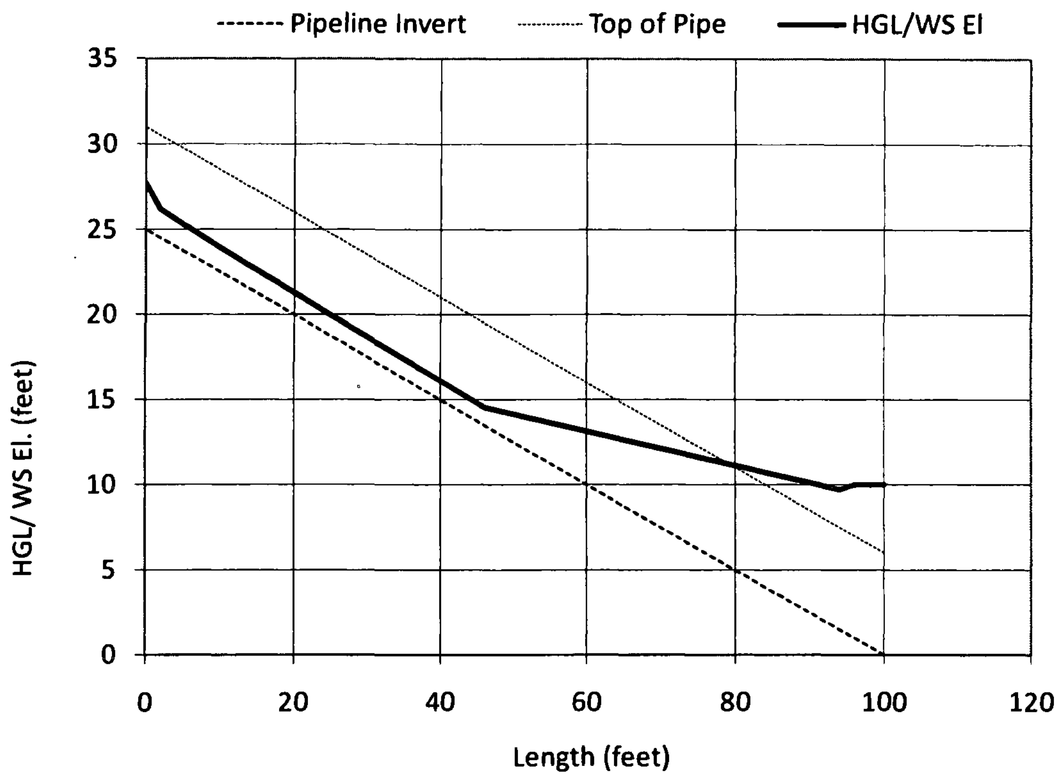


FIGURE 16. Example of steady state hydraulic profile output graph.

The final step is to input of the steady state results as initial conditions for the hydraulic transient program.

<u>Hydraulic Transient Program</u>

The hydraulic transient program is used to calculate the impact of a hydraulic transient generated by the movement of a valve at the downstream end of the pipeline.

The user input for the hydraulic transient program is shown in Table 4.

TABLE 4. Hydraulic Transient Program Unser Input

User Input	Symbol	Units
Pipe Young's Modulus of Elasticity	E	lb/ft^2
Pipe Steel Thickness	t	in
Fluid Density	ρ	$slugs/ft^3$
Water Bulk Modulus of Elasticity	K	lb/ft^2
Psi	ψ	-
Poisson's Ratio	ν	-
Simulation Time	T	seconds
Starting Time for Valve Movement	t_i	seconds
Time of Closure/Opening	t_c	seconds
Initial Tau (valve coefficient)	τ_i	seconds
Final Tau (valve coefficient)	τ_f	seconds

The information is grouped into two categories: information on the pipe and fluid (used to calculate the wave speed, *a,* and information on the simulation parameter. The program takes into account the valve movement. In addition the valve can be specified to initiate movement at any given time and complete movement within a specified time. For example, the user can specify that the valve will start to move 3 secondsafter the simulation has started and will change from 100-percent open to 50-percent open in a total time of 5 minutes.

Table 5 shows the Excel data that is calculated using the user input.

TABLE 5. Hydraulic Transient Excel Calculated Information

Excel Calculated Information	Symbol	Units
Wave Speed	a	feet per second
Pipeline Characteristic Impedance	C_a	-
Pipeline Resistance Coefficient	R	-
Time Step Size, dt	Δt	Seconds
Valve Initial C_v	C_{vi}	-

It is important to note that the time step for the simulations, *dt*, is automatically calculated based on a *Courant-Friedrich-Lewy* stability number, C_N equal to one.

The equation for the *Courant-Friedrich-Lewy* stability number is:

$$C_N = \frac{a}{\Delta x/\Delta t} = \frac{a\Delta t}{\Delta x} \qquad (5\text{-}3)$$

therefore the *dt* for the hydraulic transient simulation is calculated as:

$$dt = \frac{\Delta x}{a} \qquad (5\text{-}4)$$

If the *dt* does not satisfy the condition set by equation 5-4, the results may not be accurate for this program. The characteristic lines will not intersect and the predicted values will not converge on a proper solution.

The initial value of C_v is based on the initial value of τ. This accounts for situations where the valve may be partially closed at the start of the simulation. The value of C_v is modified based on the following equation:

$$C_V = \frac{C_{v\,full\,open}}{\tau} \qquad (5\text{-}5)$$

In the future, additional functionality may be added to the program to allow the user to enter various types of pipelines based on the elastic properties of the pipeline (ψ, non-dimensional parameter of the pipe). This could account for various types of pipeline systems such as rigid conduits, thick-walled conduits, tunnels, reinforced concrete pipes, and PVC pipes.

The hydraulic transient program consists of a main routine, which calls up several subroutines to complete calculations. The subroutines calculate the transient conditions in the pressurized section of the pipe, the free-surface hydraulic computations, the boundary condition information, and the internal boundary condition movement. The overall routine is presented on the flow chart in Figure 17. Each of the four subroutines utilize the numerical methods described in chapter 4. The program proceeds through each time step and incremental length and calculates H and Q at each node and boundary condition. See Figure 14 for a graphical representation of the order in which the calculations proceed. A sample of the spreadsheet tab used for the calculations is shown in Appendix B. In addition to the numerical output, four graphical outputs are also presented.

The graph shown in Figure 18 shows the pipeline profile along with the steady state HGL/WSP, the envelope curve (maximum HGL/WSP and minimum HGL/WSP) and the current HGL/WSP for each time step. During the transient simulation, the program will update the results to animate the movement of the HGL/WSP for current time step. At the downstream valve location, the piezometric head, H, is plotted with respect to time as shown in Figure 19.

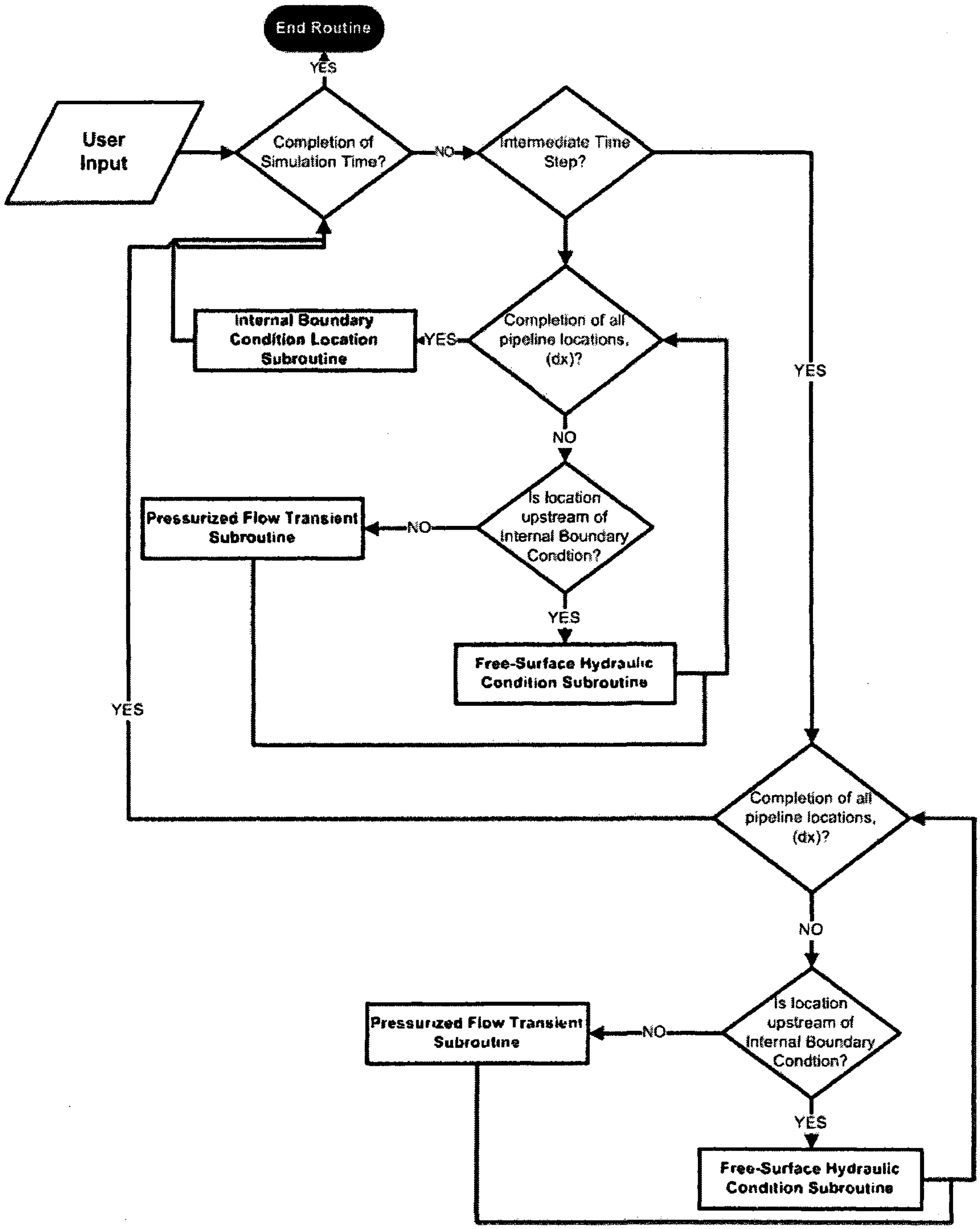


FIGURE 17. Hydraulic transient program flow chart.

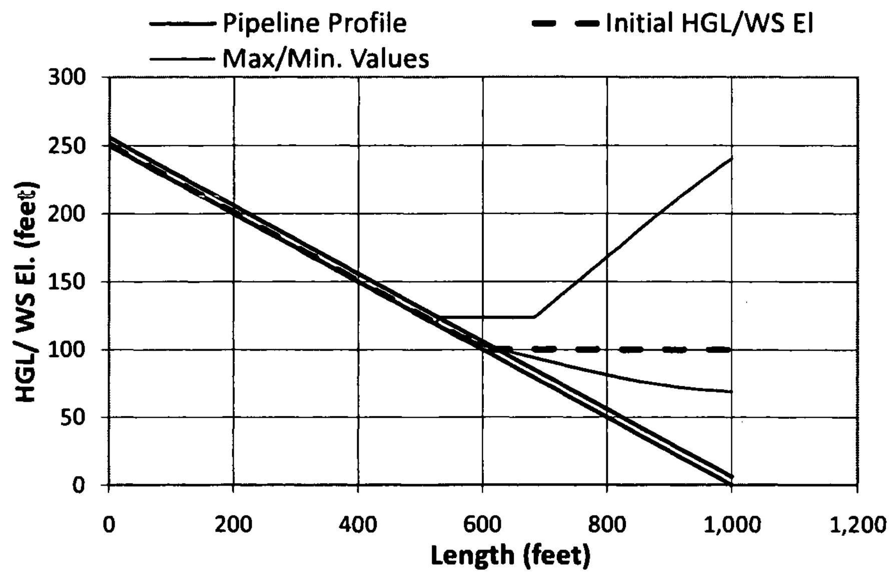


FIGURE 18. Hydraulic transient program envelope curve vs. time.

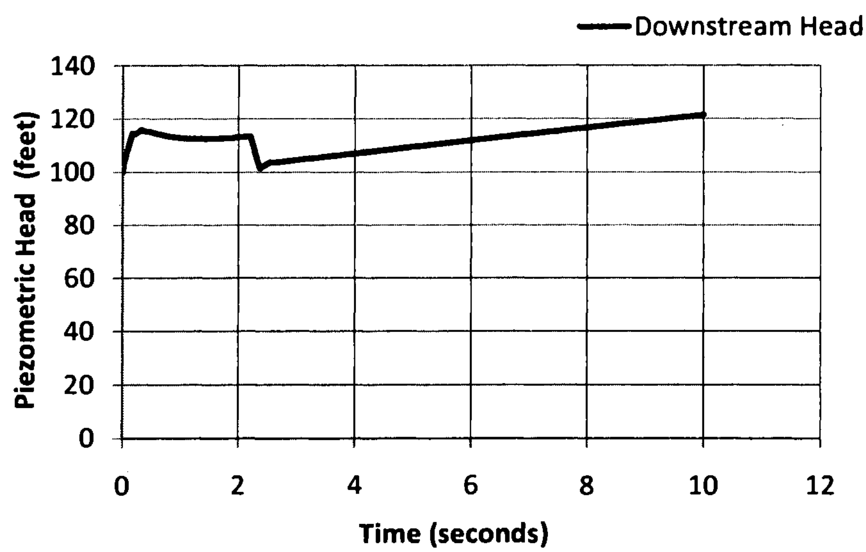


FIGURE 19. Hydraulic transient program downstream head graph.

The valve movement with respect to time is plotted as shown in Figure 20, and finally, the movement of the free-surface/pressurized transition is plotted with respect to time as shown in Figure 21.

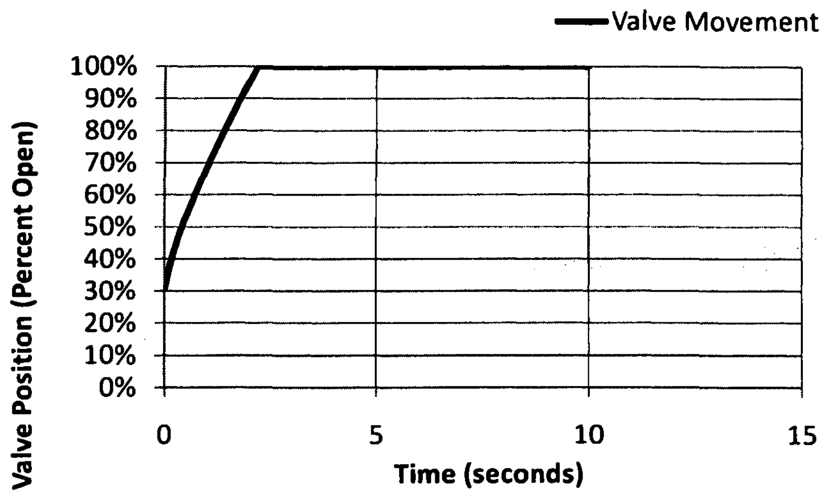


FIGURE 20. Hydraulic transient program valve movement graph.

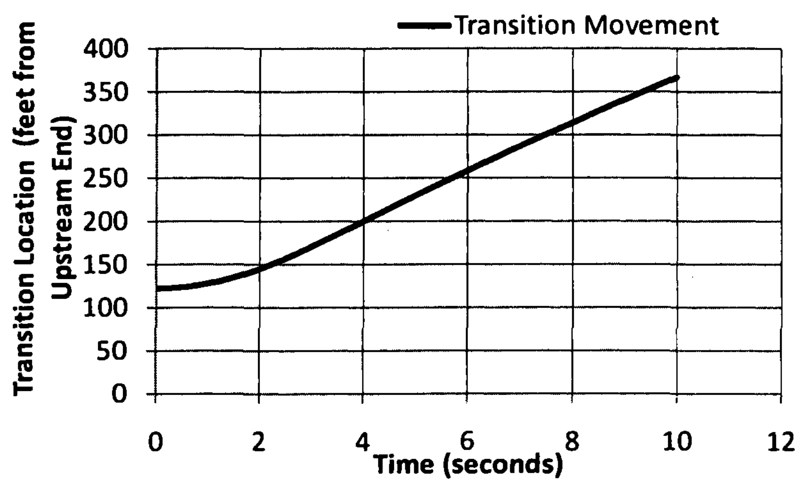


FIGURE 21. Hydraulic transient program transition location graph.

Model Comparison

The developed computer program results were compared to results that have been validated and reflected in the literature. This author is not aware of any published data on hydraulic transients in CFSPF pipelines with supercritical flow. However, data for pressurized flow hydraulic transients is available from Wylie and Streeter (1993). The authors modeled a single pipeline with a downstream valve (discharging to atmosphere) with a FORTRAN computer program titled "SINGLE.FOR". The simulation parameters for the Wylie and Streeter model, which were input into the hydraulic transient program, are shown in Table 6.

TABLE 6. Input Parameters from Wylie and Streeter

Input Parameter	Value	Units
Pipeline Length	600	meters
Pipeline Diameter	0.5	meters
Initial Flow Rate	0.47	cubic meters per second
Downstream Water Surface Elevation	143.39	meters
Upstream Reservoir Water Surface Elevation	150.0	meters
Wave Speed (a)	1,200	meters per second
Friction Factor (Darcy Weisbach)	0.018	-
Valve Time of Closure	2.1	seconds
Initial Valve Position	100	percent open
Final Valve Position	0	percent open

The results from the Wylie and Streeter model were available for comparison. The same input parameters used in the Wylie and Streeter model were converted to US Customary units and input into the computer program developed for this research. A comparison of the results from both computer programs showing head, H, at the downstream valve location are shown in Figure 22. The results of the computer program developed for this research are within 0.60-percent, on average, of the Wylie and Streeter model results. Therefore, the hydraulic transient computer program developed for this research was validated for pressurized flow hydraulic transients.

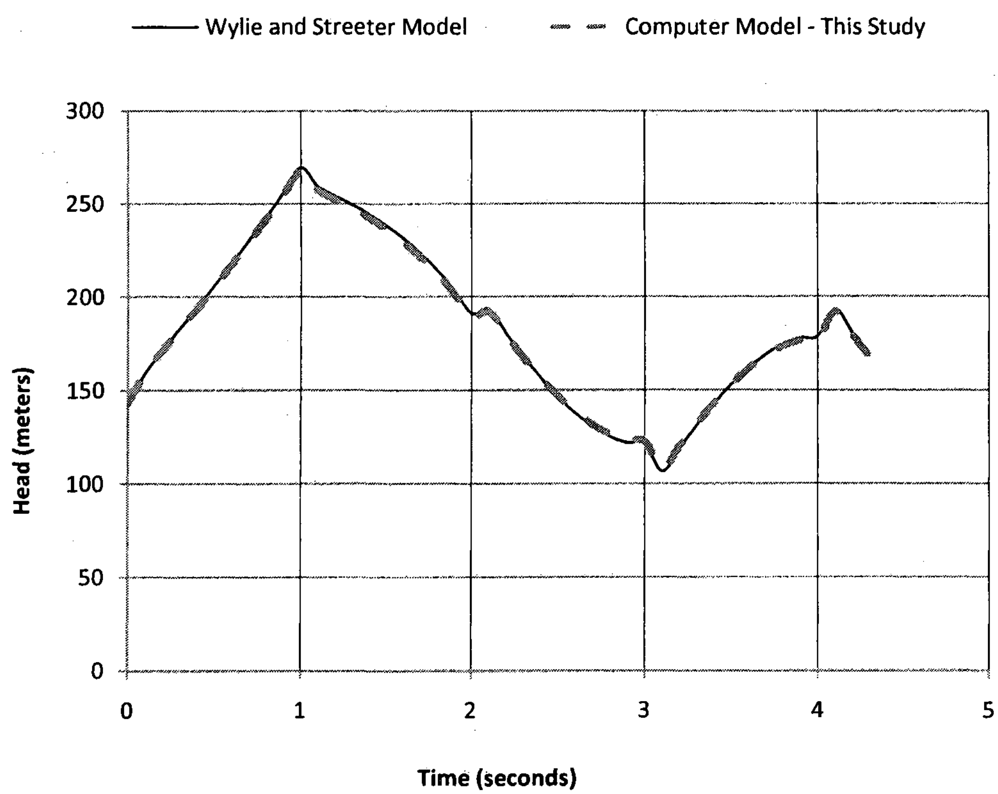


FIGURE 22. Comparison of computer program results.

Computation Step Selection

The number of computation steps selected will determine the incremental length, *dx*, used for calculation in the model. The timestep will be calculated from equation 5-4. If a large number of computational steps are chosen, the value of *dx* will be small and the timestep will be very small. The computational run time will be faster, however the results may not be accurate. Since the latest version of Excel (2007 version) allows a larger number of rows and columns for data storage and retrieval, computations were chosen to allow for a small *dx*. Several scenarios were run using the computer model to test the impact of a smaller *dx* on the results. As shown in Figure 23, a *dx* of 4-feet is sufficiently small to capture the results compared to a *dx* of 2-feet or smaller which will make the simulations more computationally intensive.

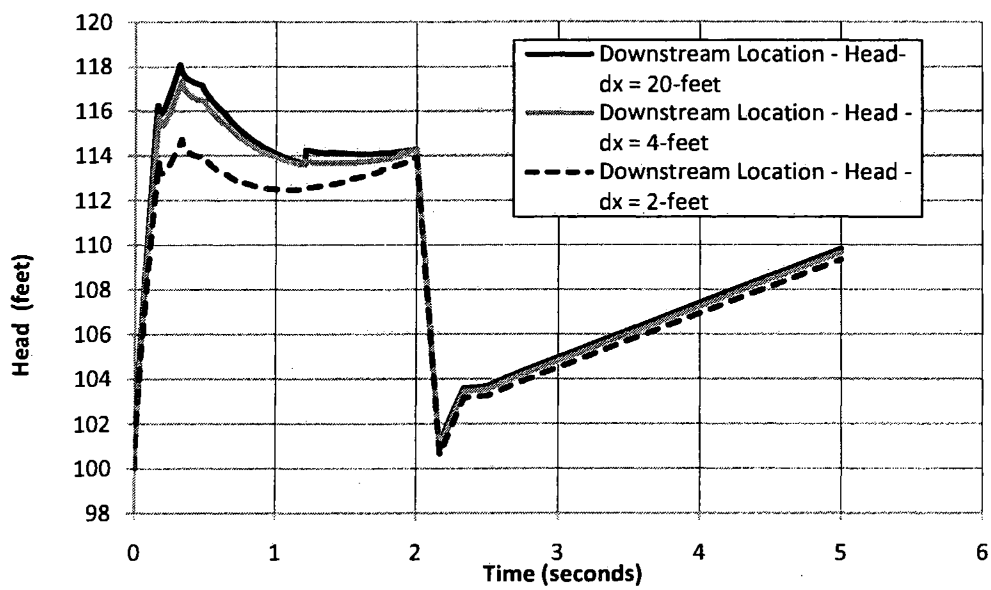


FIGURE 23. Computer program simulations with various values of dx.

CHAPTER 6

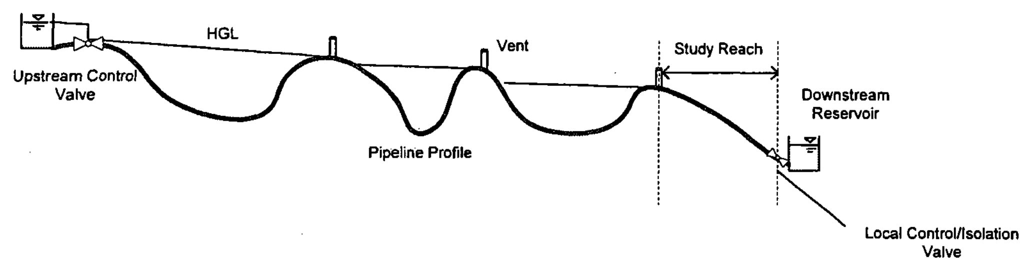
SIMULATION RESULTS

This chapter presents the results of two cases that were analyzed using the computer program.

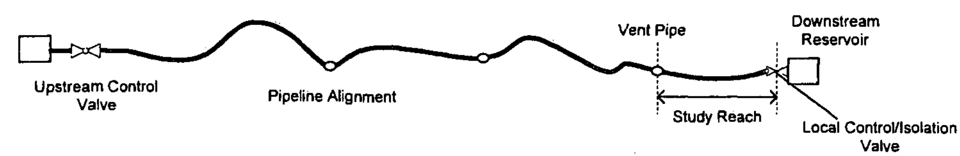
Several simplifications were made to the model used in this study compared to a typical prototype examples. The prototype would be a large-diameter water transmission pipeline that is tens of miles long. The model studies only a specific reach of these water transmission pipelines. The reach under study has been separated from the pipeline system and is only a few thousand feet long. The reach that is modeled for this study is laid on a steep slope downstream of a high point such as a hill. Downstream of the studied area the pipeline would discharge into a fixed head reservoir. The model reach compared to a typical prototype is shown in

Figure 24. Upstream of the modeled reach the pipeline approaches the high point on a horizontal or adverse slope. The flow will become free-surface flow. The model begins with a free-surface flow at a depth equal to critical depth. Atmospheric pressure in the free-surface flow area is assumed due to the large vent. A valve is located in the studied reach even though flow in the system is controlled at an upstream as shown in

Figure 24.



a.) Typical Prototype Pipeline Profile



b.) Typical Prototype Pipeline Plan

Figure 24. Comparison between prototype and model.

The valve in the study reach represents a control valve that has been placed in the pipeline for isolation purposes or for localized control in a cascading reach (Whitsett 1969). The study assumes the valve is inadvertently closed or opened under an abnormal operation or the valve has mechanically failed and slammed shut. At the downstream end of the study reach, the pipeline discharges to a constant head reservoir.

Case 1 is a scenario in which the downstream valve shuts completely and the hydraulic transients generated are simulated along with the movement of the free-surface/pressurized transition. For Case 1, five variations will be introduced to the baseline case to perform a sensitivity analysis on the factors that affect the movement of the free-surface/pressurized interface. Similarly, Case 2 presents the same data and similar variations; however, in this case the downstream valve is opening.

Case 1: Downstream Valve Closure

Case 1 is a simulation in which the downstream valve in the CFSPF study reach shuts. Case 1 will be considered the base simulation for comparison with five other scenarios obtained by varying several parameters. The first two variations, known as Case 1A and Case 1B, analyze two closure times. For Case 1A, the time of closure is decreased to cause the valve to close faster. In Case 1B the time of the valve closure is increased to cause the valve to close slower. Cases 1C and 1D will be analyzed based on the valve position (the τ factor). Case 1C will consider the final valve position to be greater than the base case. In Case 1D the final valve position will be less than the base case. Finally, Case 1E will consider a pipeline with a steeper slope than the base case.

For Case 1, the valve closure generates a hydraulic transient at the downstream end, which propagates upstream. The wave is reflected back and forth between the valve and the transition and dampened with time due to the friction in the pipeline. The valve closure also decreases the total flow out of the pipeline. Therefore, the internal boundary condition moves upstream as the pipeline fills with water. The user inputs for Case 1 are shown in Table 7. The actual time for the generation of results was approximately 30 minutes, which was a typical result for all cases.

The envelope curve for the simulation is shown in Figure 25. Table 8 summarizes some selected results of Case 1. The results for valve closure, downstream head and free-surface/pressurized interface movement are presented later together with Cases 1A and 1B for comparison.

TABLE 7. Input Parameters for Case 1

Input Parameter	Value	Units
Pipeline Length	2,000	feet
Pipeline Diameter	72	inches
Pipeline Steel Thickness	0.5	inches
Pipeline Slope	0.25	feet/feet
Normal Depth	0.85	feet
Critical Depth	2.71	feet
Number of Sections for Computation	200	-
Incremental Length, *dx*	10	feet
Timestep, *dt*	0.00395	seconds
Initial Flow Rate	100	cubic feet per second
Downstream Water Surface Elevation	300	feet above mean sea level
Upstream Water Surface Elevation	502.7	Feet
Wave Speed (a)	2,531	feet per second
Friction Factor (Darcy Weisbach)	0.020	-
Total Simulation Time	60	seconds
Valve Time of Closure	15	seconds
Initial Valve Position	100	percent open
Final Valve Position	30	percent open

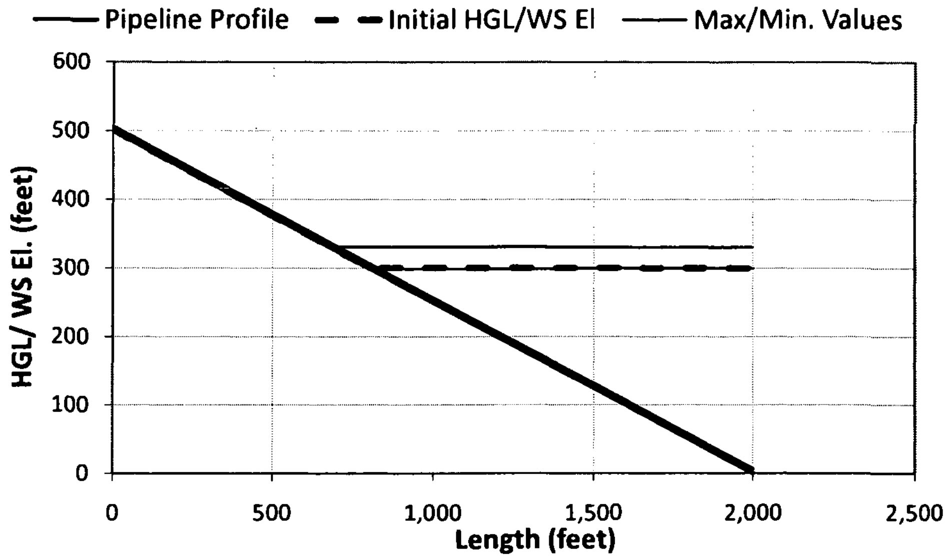


FIGURE 25. Case 1 envelope curve.

TABLE 8. Selected Results for Case 1

Result	Value	Units
Total Transition Movement (Upstream)	127	feet
Velocity of Free-Surface/Pressurized Transition at t=60 seconds	2.4	feet per second
Downstream Flow at t=60 seconds	31.5	cubic feet per second

Case 1A and 1B: Change in Downstream Valve Closure Time

Case 1A and 1B consider the impact of valve closure time. In addition, the impact to the movement of the free-surface/pressurized transition is analyzed. Physically, Case 1A and Case 1B represent closing of the valve at a faster or slower rate compared to the base case. The time of closure for Case 1A was chosen so the closure time would be near the critical closure time of a valve of *2L/a* and would represent the mechanical failure of the valve. For this scenario, the critical time of closure was 1.6-seconds. The time of closure for Case 1B was selected to be about 20 times the critical time of closure. This case, along with Case 1, represents the inadvertent fast closure of the valve in a prototype system. The Table 9 shows the parameters that were modified for Case 1A and Case 1B as compared to Case 1.

TABLE 9. Input Parameters for Case 1A and Case 1B

Input Parameter	Value	Units
Case 1A:		
Valve Time of Closure	5	seconds
Case 1B:		
Valve Time of Closure	30	seconds

The envelope curve for Case 1A and Case 1B simulation are shown on Figure 26 and Figure 27. The movement of the valve for Cases 1, 1A and 1B are shown on Figure 28. The downstream piezometric head, *H*, with respect to time for the Case 1A and Case 1B compared to Case 1 is shown of Figure 29. The location of the free-surface boundary with respect to time for Case 1A and Case 1B is shown on Figure 30. Table 10 summarizes some selected results of both cases.

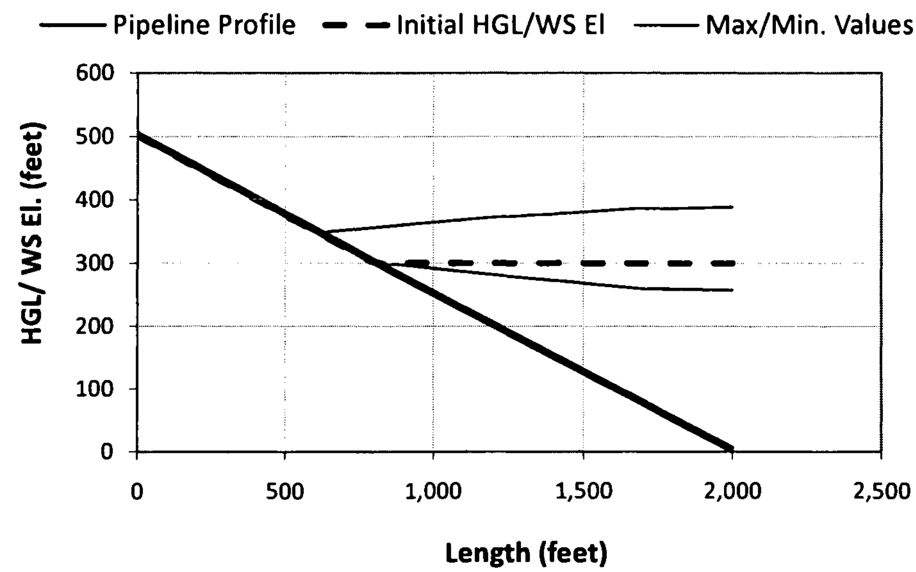


FIGURE 26. Case 1A envelope curve.

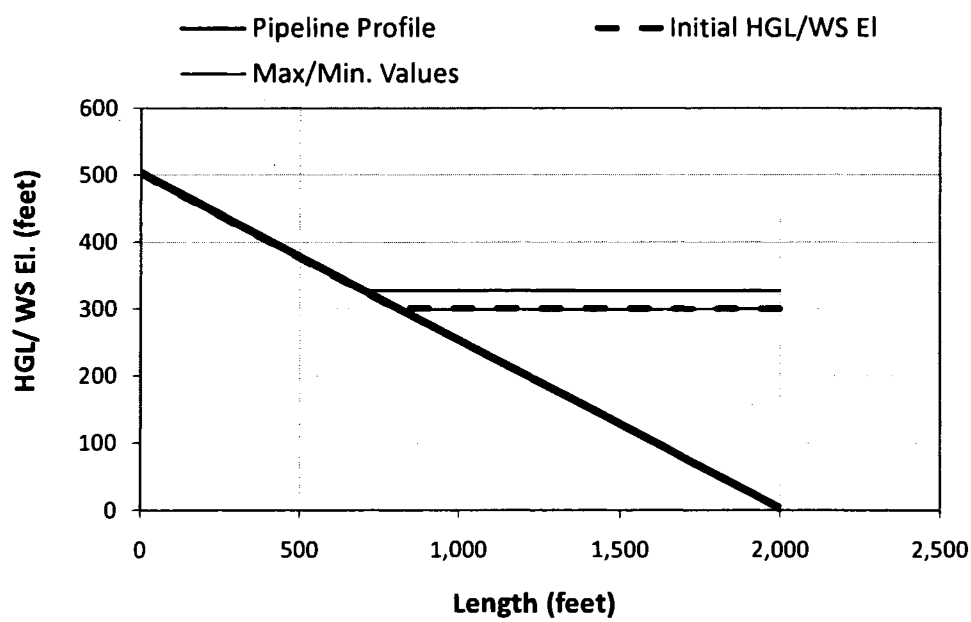


FIGURE 27. Case 1B envelope curve.

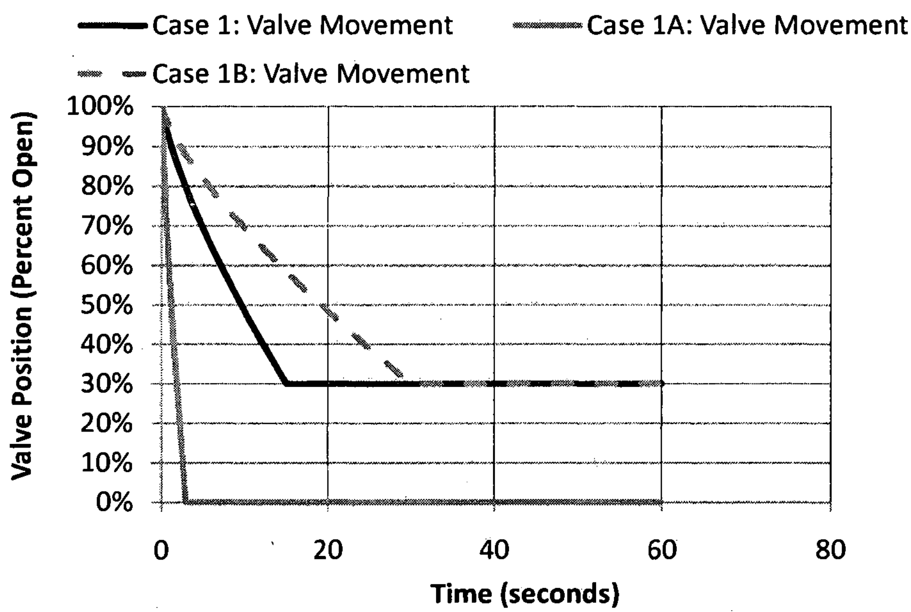


FIGURE 28. Case 1, Case 1A and Case 1B valve movement.

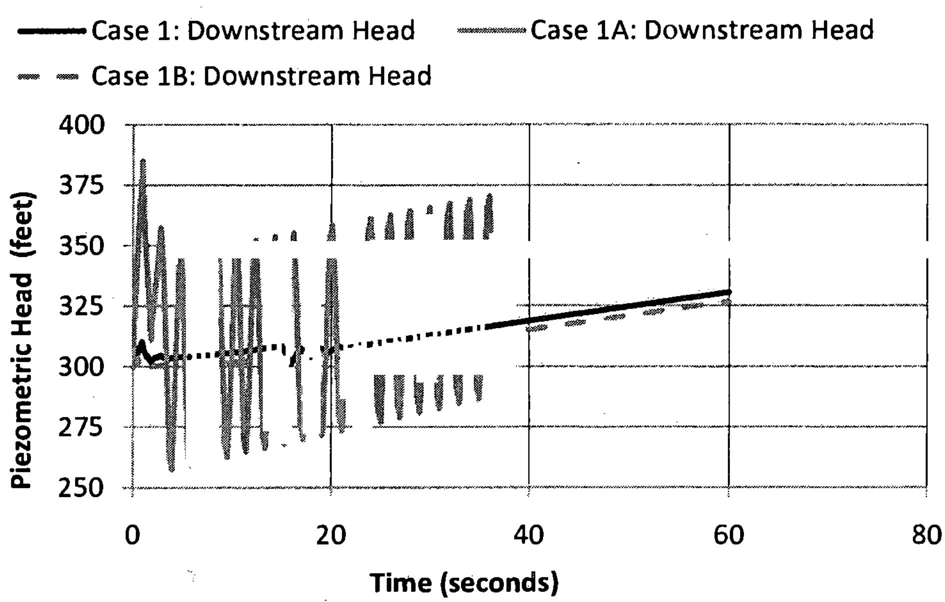


FIGURE 29. Case 1, Case 1A and Case 1B downstream piezometric head.

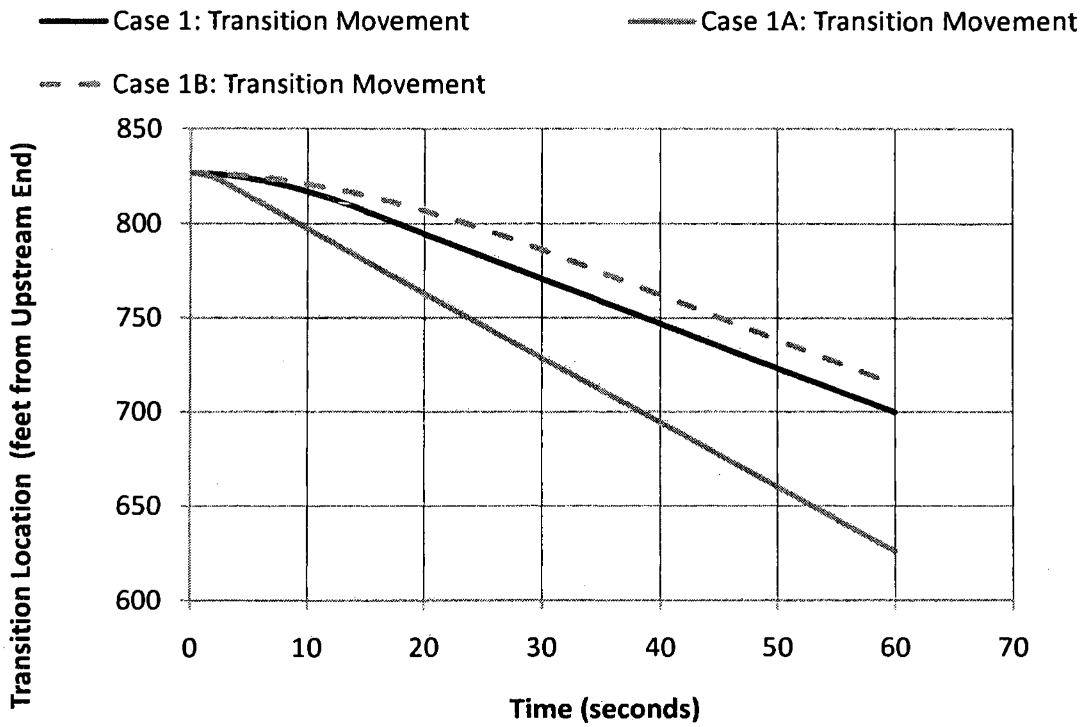


FIGURE 30. Case 1, Case 1A and Case 1B location of flow transition in time.

For all three cases, the valve closes and the downstream head increases initially, drops and then increases at a uniform rate. Because the pipe is filling the head increases in a linear fashion. The fast valve closure, Case 1A, results in large oscillations in head due to the wave reflection against a closed valve, compared to the slower valve (Case 1B) closure in which the pressure increase was smaller and the valve did not close completely. In both cases, the free-surface/pressurized transition moves at the same rate as Case 1, however in Case 1A the transition moves faster in the initial time steps. This is due to the quick reduction in flow rate during Case 1A.

TABLE 10. Select Results of Case 1A and Case 1B

Result	Value	Units
Case 1A:		
Total Transition Movement (Upstream)	201	feet
Velocity of Free-Surface/Pressurized Transition at t=60 seconds	3.4	feet per second
Downstream Flow at t=60 seconds	0	cubic feet per second
Case 1B:		
Total Transition Movement (Upstream)	112	feet
Velocity of Free-Surface/Pressurized Transition at t=10 seconds	2.4	feet per second
Downstream Flow at t=10 seconds	31.3	cubic feet per second
Case 1:		
Total Transition Movement (Upstream)	127	feet
Velocity of Free-Surface/Pressurized Transition at t=10 seconds	2.4	feet per second
Downstream Flow at t=10 seconds	31.5	cubic feet per second

Case 1C and 1D: Change in Downstream Valve Opening

Case 1C and 1D consider the impact on the results with various final valve positions compared to the base case. Physically, Case 1C and Case 1D represent the closing of the valve at the same rate as Case 1, however the final position of the valve is left at a greater or less percent open. Table 11 shows only the values of the parameters that were modified for Cases 1C and 1D as compared to Case 1.

TABLE 11. Input Parameters for Case 1C and Case 1D

Input Parameter	Value	Units
Case 1C:		
Final Valve Position	50	percent open
Case 1D:		
Final Valve Position	10	percent open

The envelope curve for Case 1C is shown in Figure 31 and the Case 1D envelope curve is shown in Figure 32. The location of the valve versus time for Cases 1, 1C and 1D are shown in Figure 33. The downstream piezometric head, *H*, with respect to time for the Case 1C and Case 1D compared to Case 1 is shown in Figure 34. The location of the free-surface boundary with respect to time for Case 1C and Case 1D is shown in Figure 35. Table 12 highlights selected results from Case 1C and 1D.

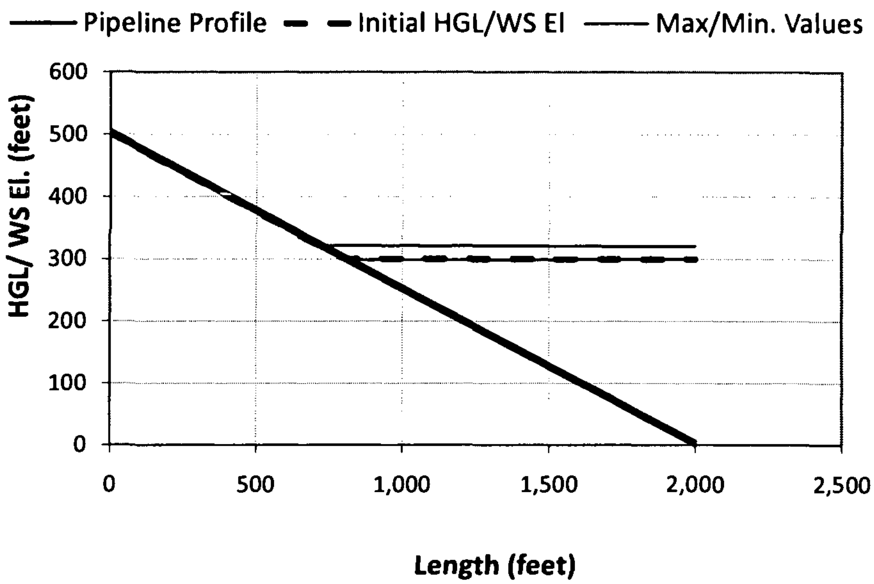


FIGURE 31. Case 1C envelope curve.

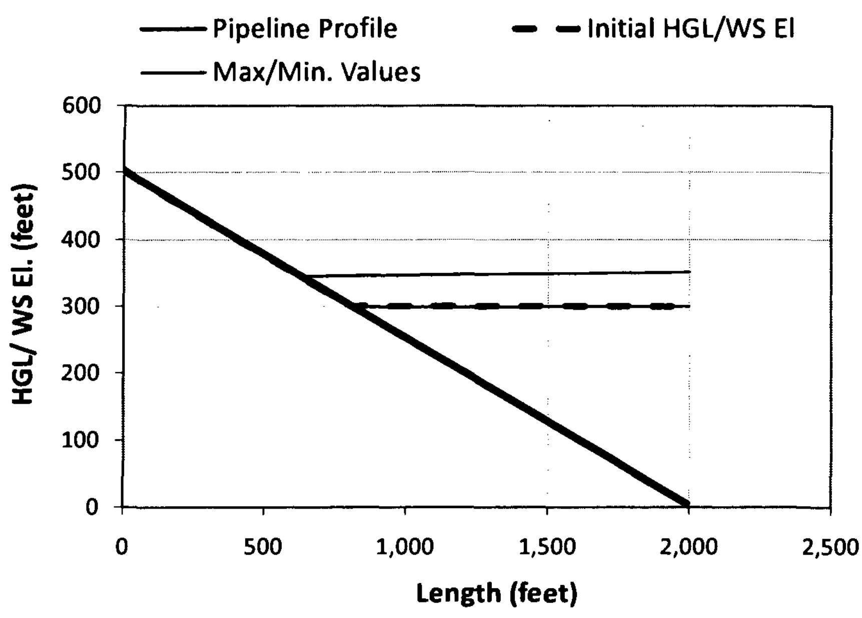


FIGURE 32. Case 1D envelope curve.

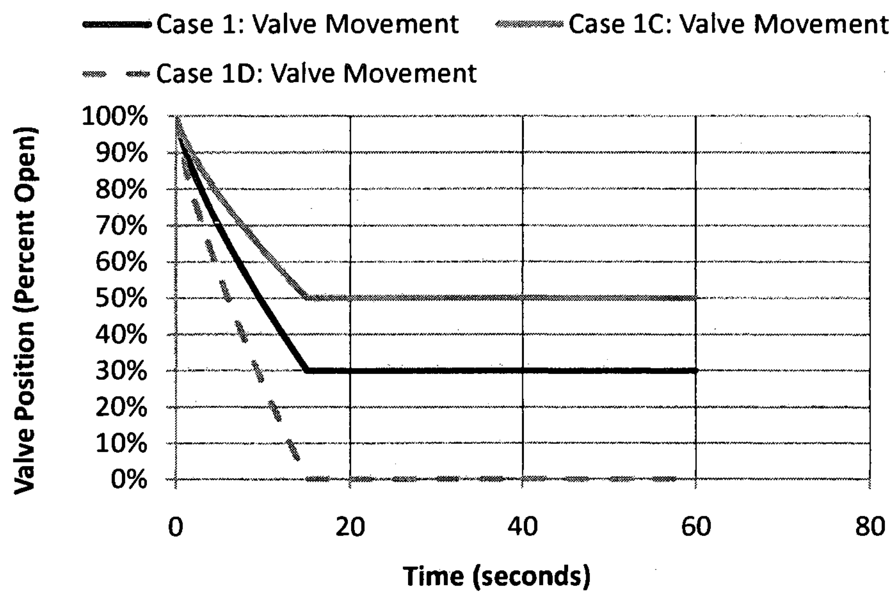


FIGURE 33. Case 1, Case 1C and Case 1D valve movement.

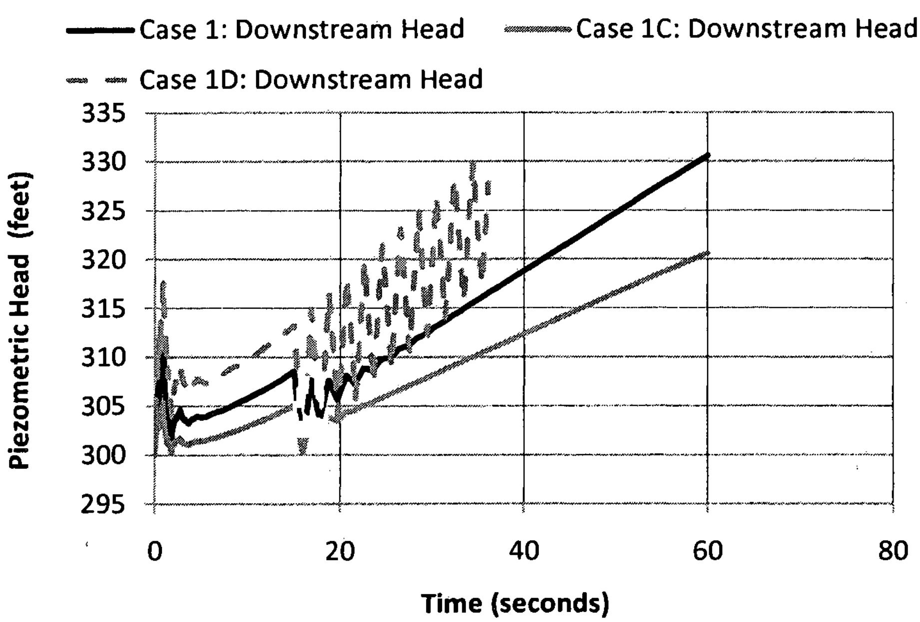


FIGURE 34. Case 1, Case 1C and Case 1D downstream piezometric head.

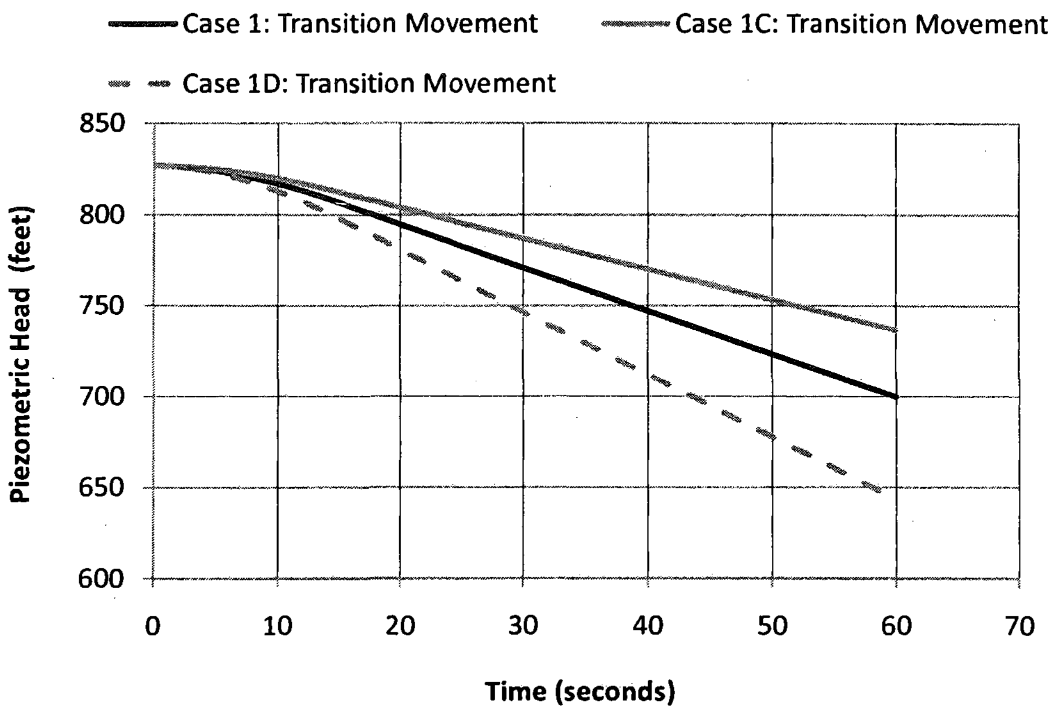


FIGURE 35. Case 1, Case 1C and Case 1D location of the flow transition in time.

The initial pressure rise due to the valve closing is greater for Case 1D and less in Case 1C compared to Case 1. This is due to the valve being closed more (less percent open) in Case 1D and causing a larger transient. Conversely, when the valve is closed less as in Case 1C, the initial pressure rise is less than Case 1. In addition, the valve is fully closed in Case 1D causing pressure waves to rapidly oscillate in the system. When examining the transition movement results, the free-surface/pressurized transition moves at a higher rate in Case 1D, due to the reduced flow out of the pipeline because of the greater valve closure. Conversely, in Case 1C the transition moves slower.

TABLE 12. Selected Results of Case 1C and Case 1D

Result	Value	Units
Case 1C:		
Total Transition Movement (Upstream)	90.3	feet
Velocity of Free-Surface/Pressurized Transition at t=60 seconds	1.7	feet per second
Downstream Flow at t=60 seconds	51.7	cubic feet per second
Case 1D:		
Total Transition Movement (Upstream)	183.5	feet
Velocity of Free-Surface/Pressurized Transition at t=60 seconds	3.4	feet per second
Downstream Flow at t=60 seconds	0	cubic feet per second
Case 1:		
Total Transition Movement (Upstream)	127	feet
Velocity of Free-Surface/Pressurized Transition at t=60 seconds	2.4	feet per second
Downstream Flow at t=60 seconds	31.5	cubic feet per second

Case 1E: Change in Pipeline Slope

Case 1E considers the impact of a change in pipeline slope compared to the base case, Case 1. The input slope for Case 1E was set to 0.5 feet/feet.

The envelope curve for Case 1E simulation is shown in Figure 36 and the downstream piezometric head, *H*, with respect to time for the Case 1E is shown in Figure 37. The location of the free-surface boundary with respect to time is shown in Figure 38. Table 13 summarizes some selected results.

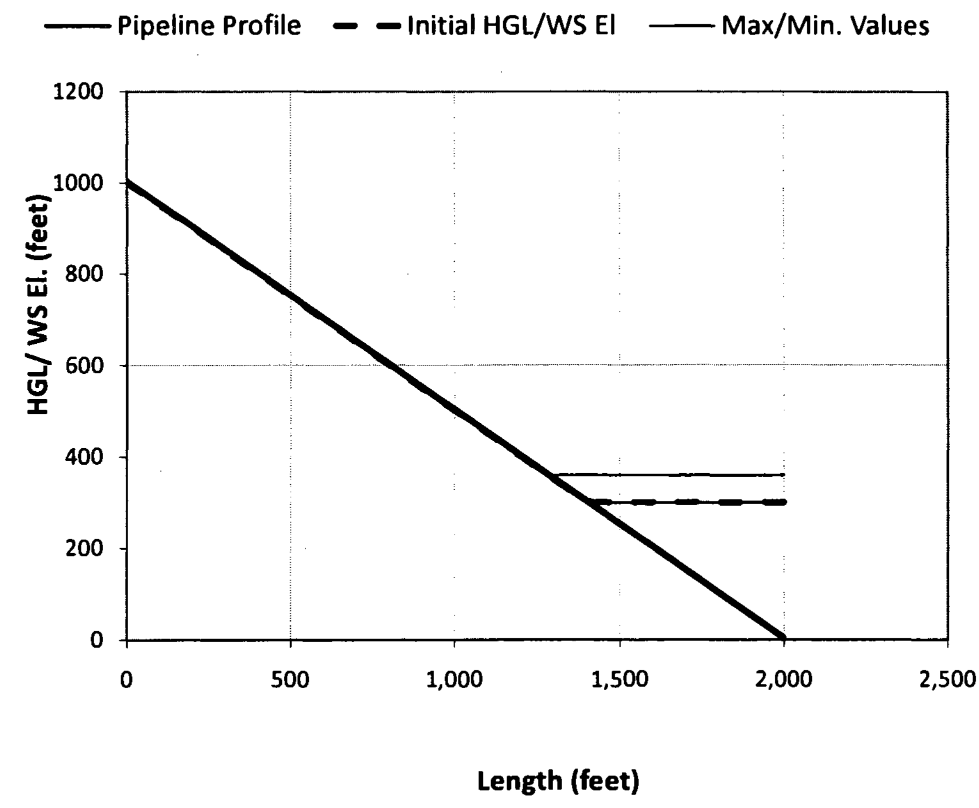


FIGURE 36. Case 1E envelope curve.

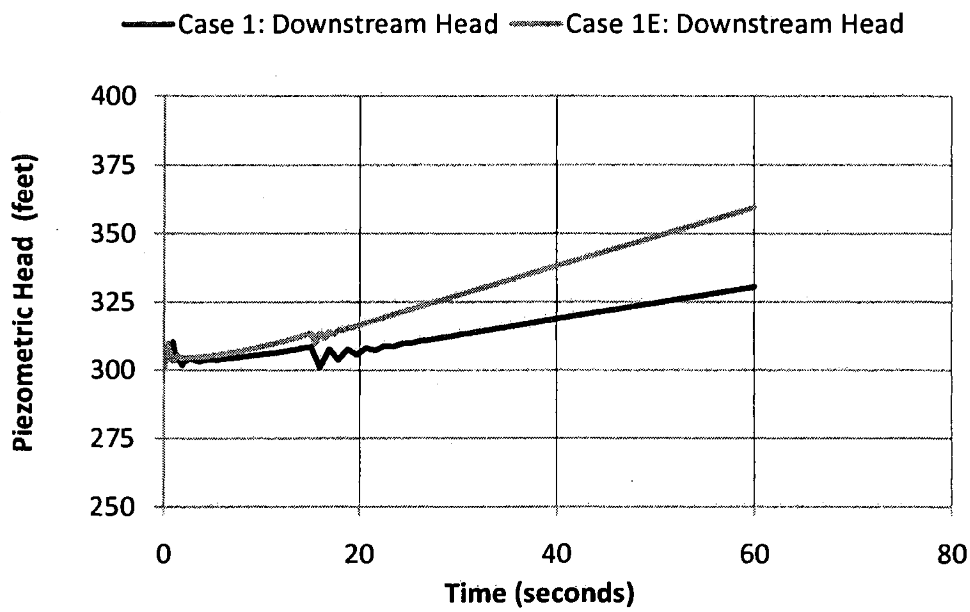


FIGURE 37. Case 1E downstream piezometric head.

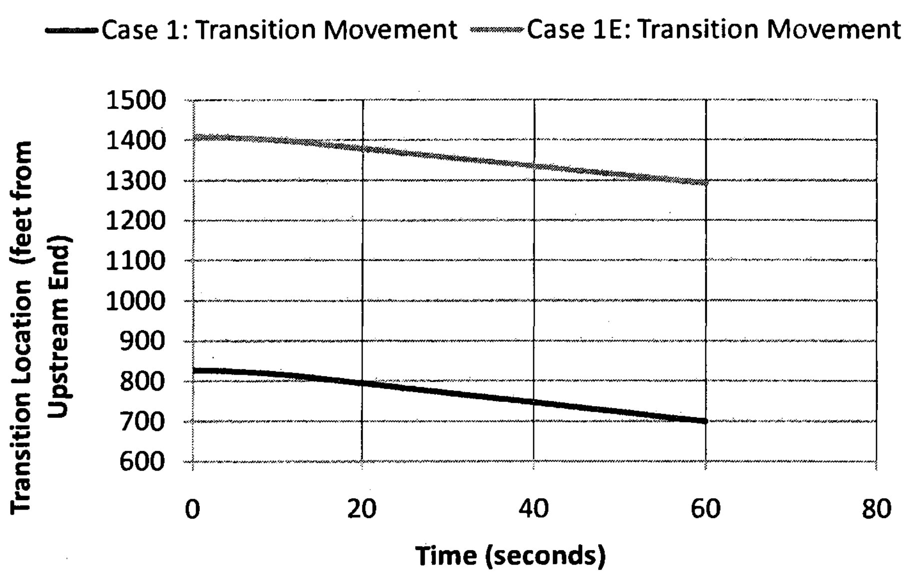


FIGURE 38. Case 1E location of flow transition in time.

TABLE 13. Select Results of Case 1E

Result	Value	Units
Case 1E:		
Total Transition Movement (Upstream)	115	feet
Velocity of Free-Surface/Pressurized Transition at t=60 seconds	2.1	feet per second
Downstream Flow at t=60 seconds	32.8	cubic feet per second
Case 1:		
Total Transition Movement (Upstream)	127	feet
Velocity of Free-Surface/Pressurized Transition at t=60 seconds	2.4	feet per second
Downstream Flow at t=60 seconds	31.5	cubic feet per second

The results indicate that there is no significant change in the values due to an increased slope. The pipeline profile and the vertical distances are different in Case 1 compared to Case 1E due to the lower slope, but the results are not significantly different.

Case 2: Downstream Valve Opening

Case 2 is a simulation in which the downstream control valve in a CFSPF pipeline is inadvertently opened. Case 2 will be considered the base simulation for comparison with five other scenarios. The first two variations, known as Case 2A and Case 2B, will analyze the variation in the opening time of the valve. For Case 2A, the time of opening is decreased to cause the valve to open faster. For Case 2B, the time of opening is increased to cause the valve to open slower. Case 2C will analyze the final valve opening position based on the τ factor. Finally, Case 2D will consider a pipeline with a steeper slope than the one in the base case.

For Case 2, the valve opening generates a downward hydraulic transient at the valve, which propagates upstream. The wave is reflected back and forth between the valve and the flow transition and dampens with time due to the friction in the pipeline. The valve opening operation increases the total flow out of the pipeline therefore the internal boundary condition moves downstream as the pipeline empties. The user inputs for Case 2 are shown in Table 14.

The envelope curve for the simulation of Case 2 is shown in Figure 39. Table 15 summarizes some selected results for Case 2.

<u>Case 2A and 2B: Change in Downstream Valve Opening Time</u>

Case 2A and 2B consider the impact of various valve opening times on the results. Physically, Case 2A and Case 2B represent opening of the valve at a faster or slower rate compared to the base case. Table 16 shows only the values of the parameters that were modified for Case 2A and Case 2B compared to Case 2.

The envelope curve for Case 2A is shown in Figure 40 and the one for Case 2B is shown in Figure 41. The valve opening for Case 2, Case 2A and Case 2B are shown on Figure 42. The downstream piezometric heads, *H*, with respect to time for Case 2, Case 2A and Case 2B are shown in Figure 43. The location of the free-surface boundary with respect to time is shown in Figure 44. Table 17 summarizes some selected results for both Cases 2A and Case 2B.

TABLE 14. Input Parameters for Case 2 Simulation

Input Parameter	Value	Units
Pipeline Length	2,000	feet
Pipeline Diameter	72	inches
Pipeline Steel Thickness	0.5	inches
Pipeline Slope	0.25	feet/feet
Normal Depth	0.85	feet
Critical Depth	2.71	feet
Number of Sections for Computation	200	-
Incremental Length, *dx*	10	feet
Timestep, *dt*	0.00395	seconds
Initial Flow Rate	100	cubic feet per second
Downstream Water Surface Elevation	300	feet above mean sea level
Upstream Water Surface Elevation	502.7	Feet
Wave Speed (a)	2,531	feet per second
Friction Factor (Darcy Weisbach)	0.020	-
Total Simulation Time	60	seconds
Valve Time of Opening	15	seconds
Initial Valve Position	30	percent open
Final Valve Position	100	percent open

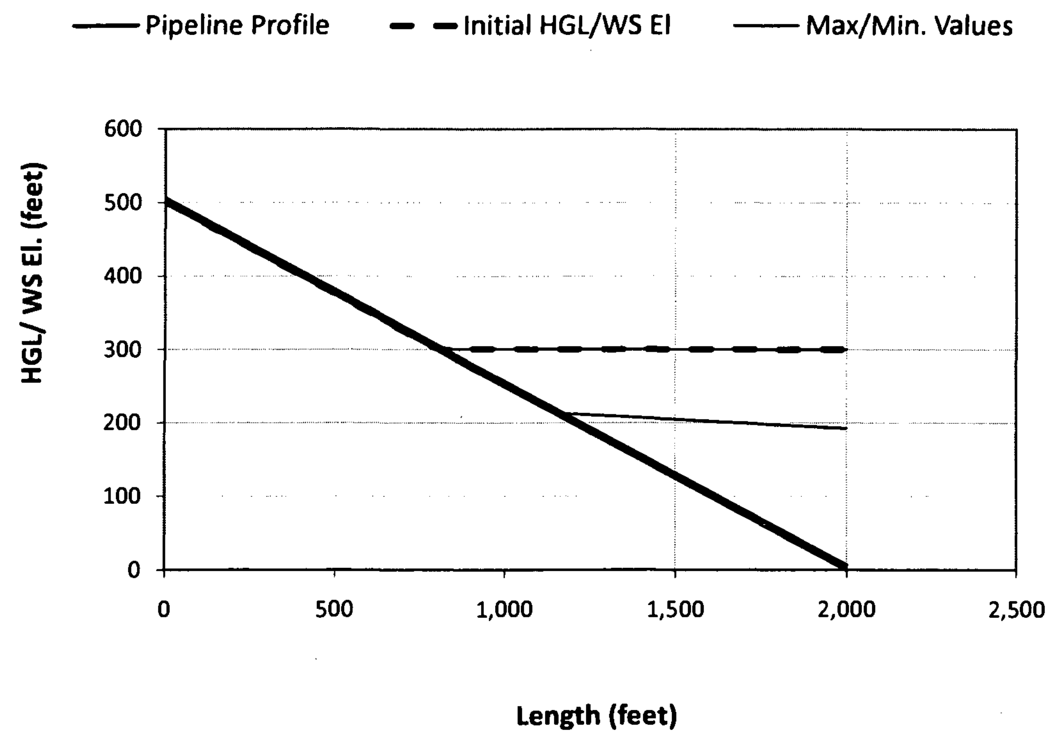


FIGURE 39. Case 2 envelope curve.

TABLE 15.Selected Results for Case 2

Result	Value	Units
Total Transition Location (Downstream)	344	feet
Velocity of Free-Surface/Pressurized Transition at t=60 seconds	5.7	feet per second
Downstream Flow at t=60 seconds	267	cubic feet per second

TABLE 16. Input Parameters for Case 2A and Case 2B Simulations

Input Parameter	Value	Units
Case 2A:		
Valve Time of Opening	3	seconds
Case 2B:		
Valve Time of Opening	30	seconds

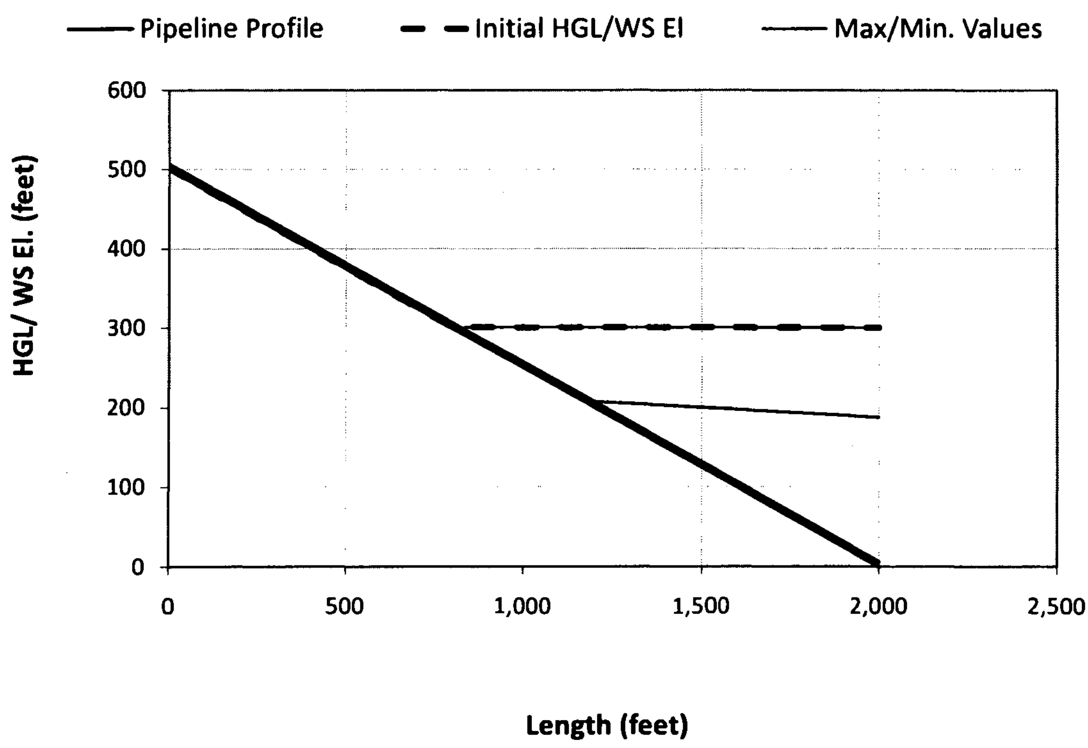


FIGURE 40. Case 2A envelope curve.

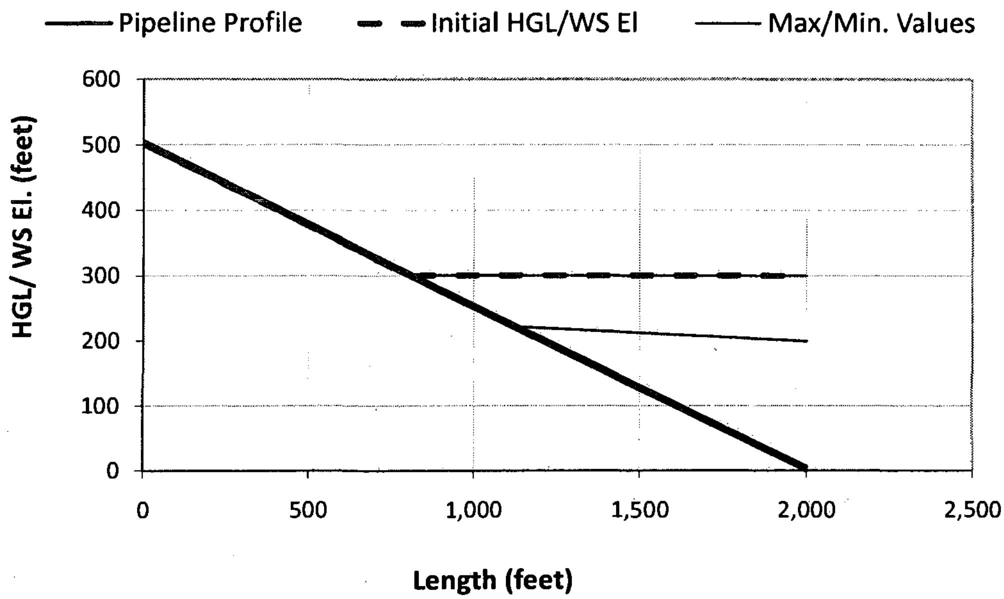


FIGURE 41. Case 2B envelope curve.

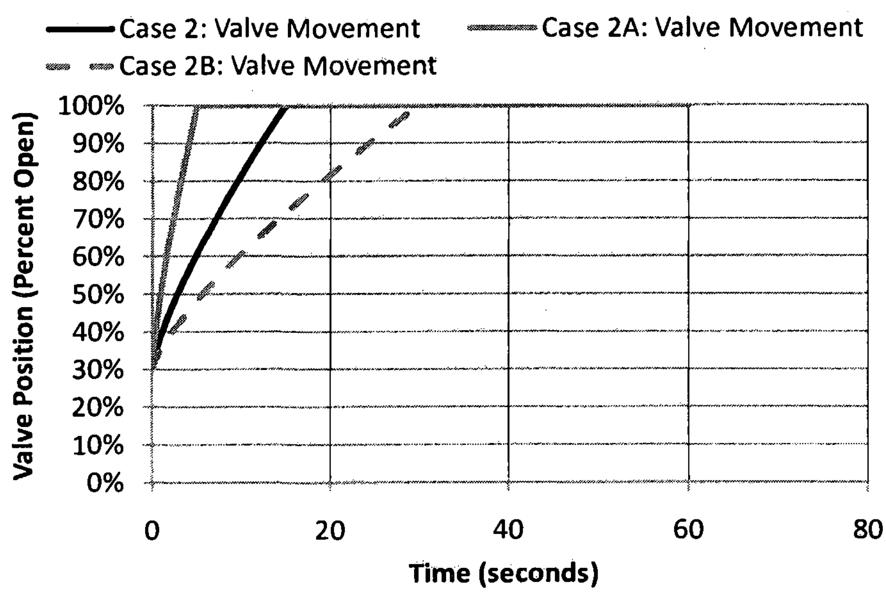


FIGURE 42. Case 2, Case 2A and Case 2B valve movement.

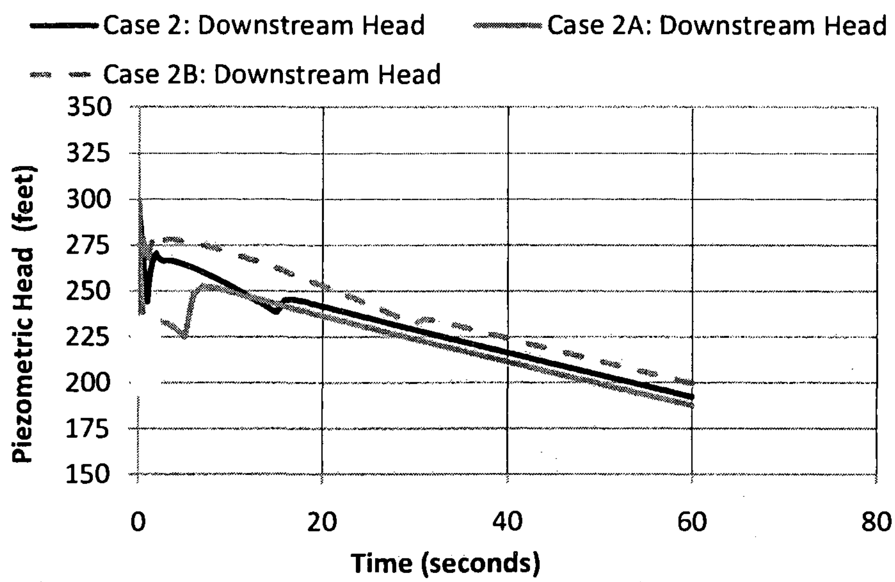


FIGURE 43. Case 2, Case 2A and Case 2B downstream piezometric head.

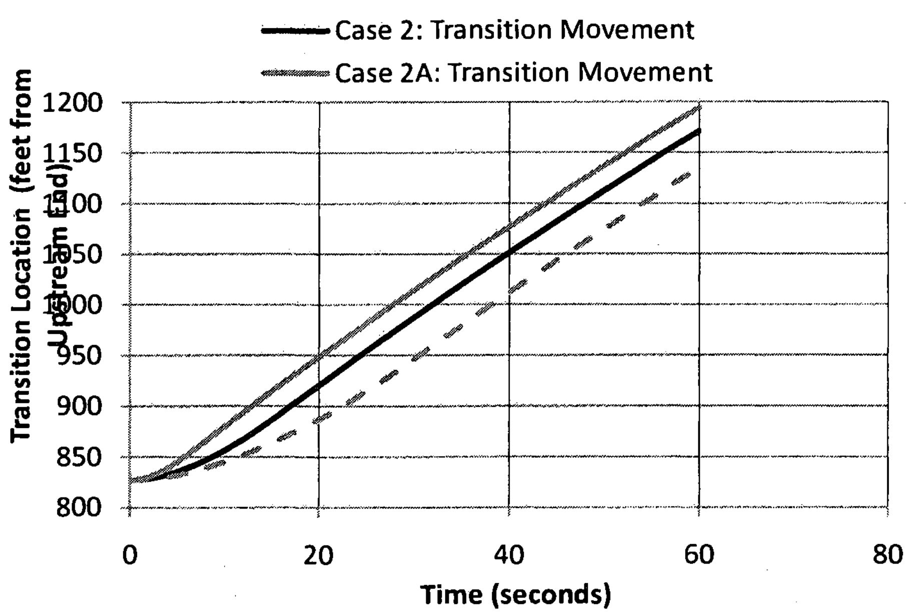


FIGURE 44. Case 2, Case 2A and Case 2B location of flow transition in time.

TABLE 17. Selected Results for Case 2A and Case 2B

Result	Value	Units
Case 2A:		
Total Transition Movement (Downstream)	368	feet
Velocity of Free-Surface/Pressurized Transition at t=10 seconds	5.6	feet per second
Downstream Flow at t=10 seconds	264	cubic feet per second
Case 2B:		
Total Transition Movement (Downstream)	308	feet
Velocity of Free-Surface/Pressurized Transition at t=10 seconds	5.9	feet per second
Downstream Flow at t=10 seconds	272	cubic feet per second
Case 2:		
Total Transition Movement (Downstream)	344	feet
Velocity of Free-Surface/Pressurized Transition at t=10 seconds	5.7	feet per second
Downstream Flow at t=10 seconds	267	cubic feet per second

In Case 2A the valve opens at a faster rate compared to Cases 2 and 2B. Case 2B has a lower down-surge when the valve opens; this is due to the slower opening time. In Case 2A the down-surge is greater than Case 2B. This is due to the faster valve movement and opening in Case 2A compared to Case 2 and Case 2B.

In addition, the faster valve movement for Case 2A causes the initiation of the free-surface/pressurized transition sooner than in Case 2B and Case 2. Case 2B movement is initiated later due to the slower rate of valve opening. However, the rate of movement of the transition is the same in all three scenarios.

Case 2C: Change in Valve Closing

Case 2C considers the impact of a decreased final opening of the valve compared to the base case. Physically, Case 2C represents the opening of the valve at the same rate as Case 2, however the at the end the valve is less open as compared to Case 2. The initial percentage opening for the valve in Case 2C was 30-percent and the final percent opening was set to 75-percent.

The envelope curve for the Case 2C is shown in Figure 45 and the valve closure is shown in Figure 46. The downstream piezometric head, *H*, with respect to time is shown in Figure 47. The location of the free-surface boundary with respect to time is shown in Figure 48. Table 18 summarizes some selected results.

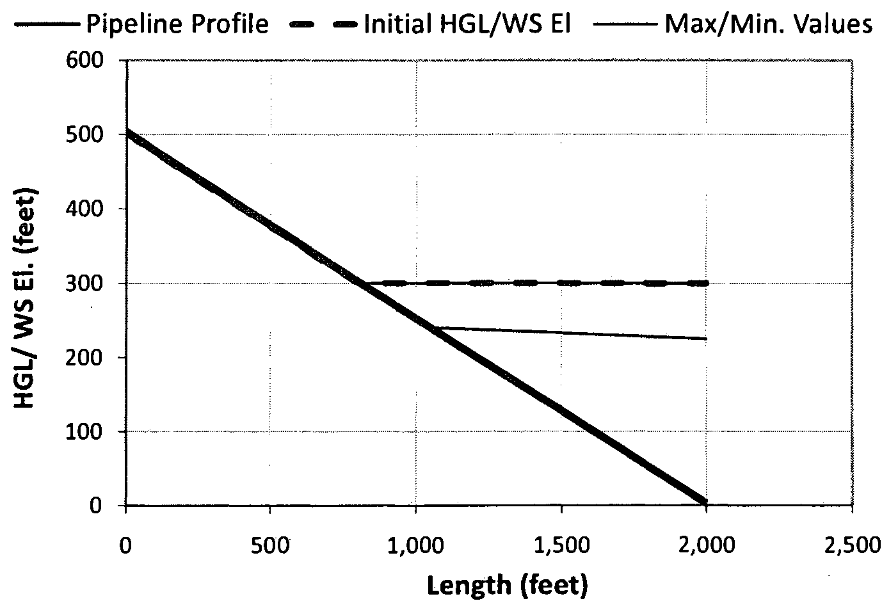


FIGURE 45. Case 2C envelope curve.

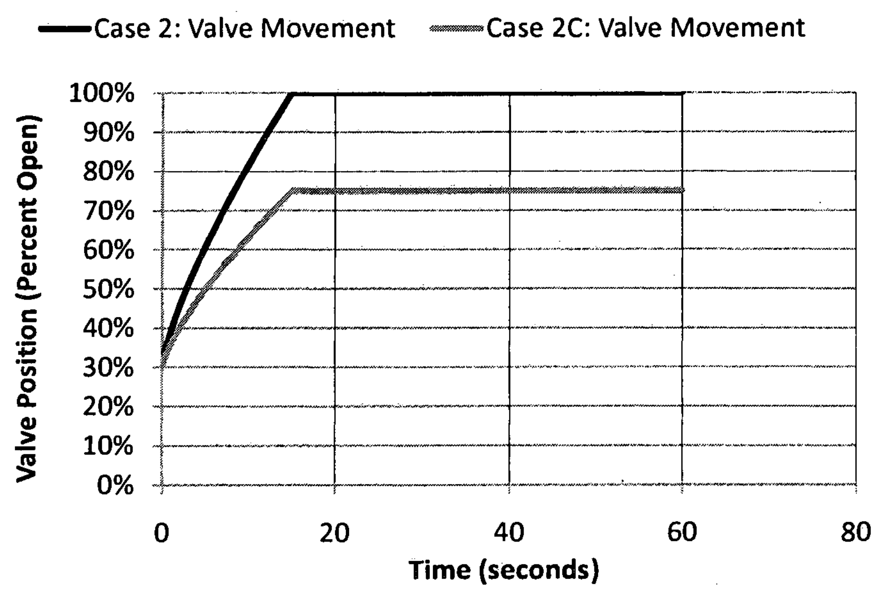


FIGURE 46. Case 2 and Case 2C valve movement.

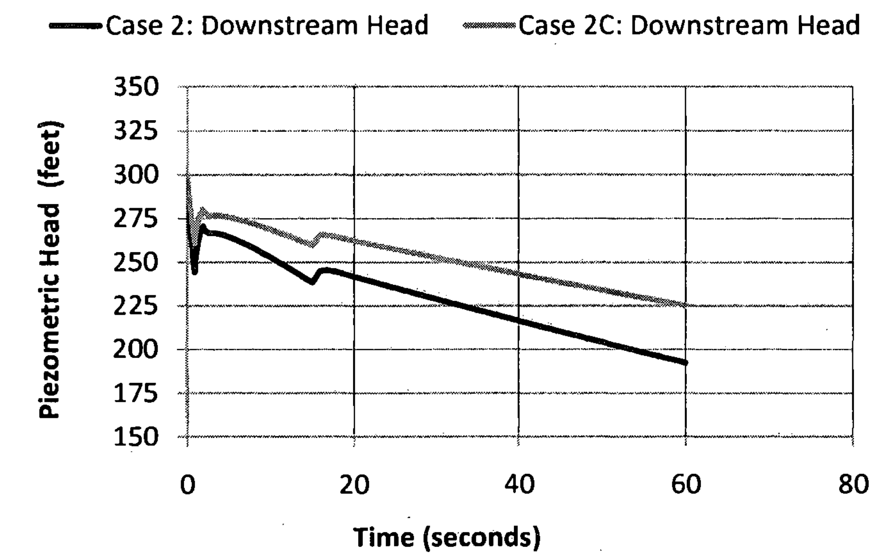


FIGURE 47. Case 2 and Case 2C downstream piezometric head.

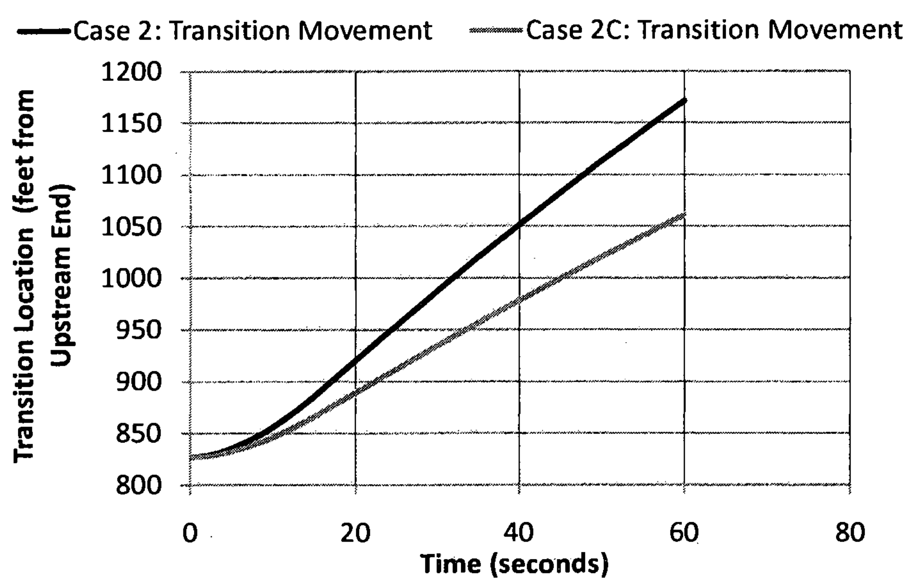


FIGURE 48. Case 2 and Case 2C location of flow transition in time.

TABLE 18. Select Results of Case 2C

Result	Value	Units
Case 2C:		
Total Transition Movement (Downstream)	234	feet
Velocity of Free-Surface/Pressurized Transition at t=10 seconds	4	feet per second
Downstream Flow at t=10 seconds	217	cubic feet per second
Case 2:		
Total Transition Movement (Downstream)	344	feet
Velocity of Free-Surface/Pressurized Transition at t=10 seconds	5.7	feet per second
Downstream Flow at t=10 seconds	267	cubic feet per second

The down-surge for Case 2C is less compared to Case 2 due the lower valve opening percentage as compared to Case 2. Although the magnitude of the down-surge in Case 2C is less, the pattern for the pressure at the downstream location is the same. The transition movement is at a faster rate compared to Case 2 because the valve is open less, therefore the pipeline will fill at a faster rate.

Case 2D: Change in Pipeline Slope

Case 2D considers the impact on the results with a pipeline greater slope compared to the base scenario. The input slope for Case 2D was set to 0.5 feet/feet compared to 0.25 feet/feet in the previous cases.

The envelope curve for Case 2D simulation is shown in Figure 49 and the downstream piezometric head, *H*, with respect to time for the Case 2D is shown in Figure 50. The location of the free-surface boundary with respect to time for Case 2D is shown on Figure 51. Table 19 summarizes some selected results.

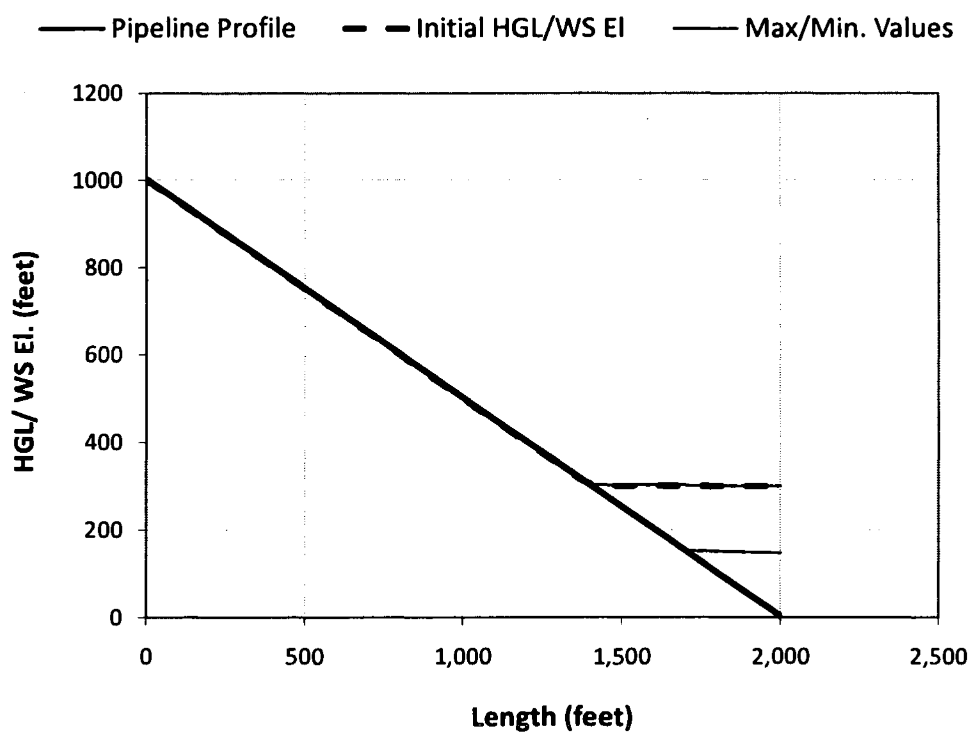


FIGURE 49. Case 2D envelope curve.

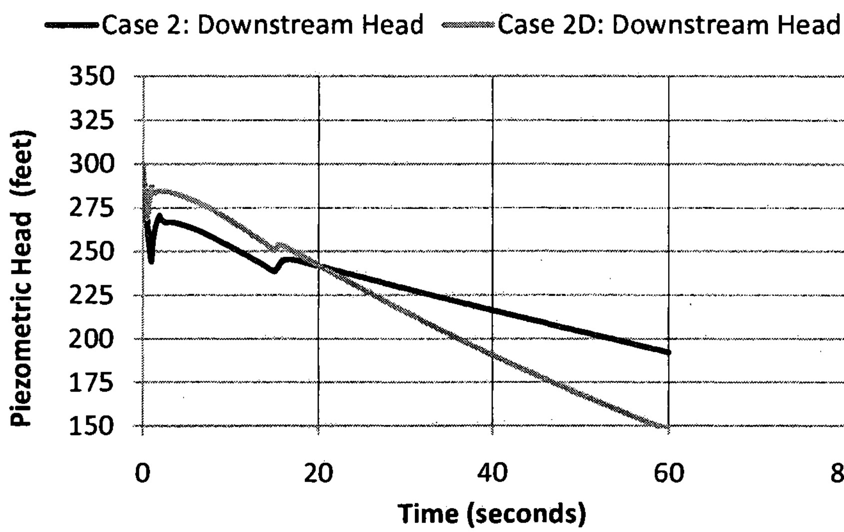


FIGURE 50. Case 2D downstream piezometric head.

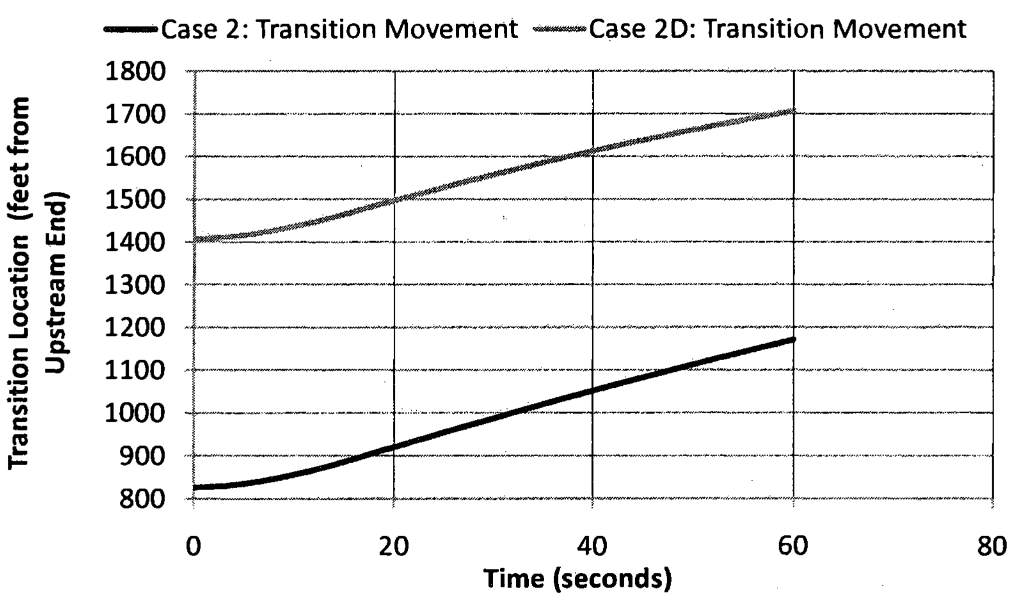


FIGURE 51. Case 2D location of flow transition in time.

TABLE 19. Select Results of Case 2D

Result	Value	Units
Case 2D:		
Total Transition Movement (Downstream)	299	feet
Velocity of Free-Surface/Pressurized Transition at t=10 seconds	4.2	feet per second
Downstream Flow at t=10 seconds	234	cubic feet per second
Case 2:		
Total Transition Movement (Downstream)	344	feet
Velocity of Free-Surface/Pressurized Transition at t=10 seconds	5.7	feet per second
Downstream Flow at t=10 seconds	267	cubic feet per second

The results indicate that the initial down-surge for Case 2D is less than Case 2. This is because the total length of pressurized flow for Case 2D was less than the length of Case 2 due to the increase slope of Case 2D. The pressure wave will move upstream and reflect back downstream at a faster rate. This causes the wave to dissipate faster and produce less of an initial down-surge.

CHAPTER 7

CONCLUSIONS

Conclusion

This study developed a pressurized flow hydraulic transient model to analyze CFSPF pipelines with free-surface supercritical flow. The model simulated both pressurized flow and free-surface flows and hydraulic transients generated in the pressurized section of the pipeline. Hydraulic transients in free-surface flow were not modeled as part of this research. The computer program was able to generate results for several scenarios and the data was presented. The research presents information on hydraulic transient propagation and how the hydraulic transients interface with the pressurized/free-surface transition. In the future, this model should be validated with field data that was not available at the time the work was completed.

Recommendations for Future Research

Several issues can be considered for future research of CFSPF pipelines. Future effort should focus on ways to integrate a numerical scheme for supercritical, free-surface flow with the pressurized flow numerical scheme developed in this research. Based on the literature available, the most suitable numerical scheme for free-surface, supercritical flows may be the Gabutti explicit scheme. According to Chaudhry (2008), this scheme allows for the analysis of supercritical flows. In addition, the second-order explicit schemes like the Gabutti explicit scheme are superior in reproducing shocks and bores (Chaudhry 1987). In this research the Lax numerical method for free-surface transients was programmed, but the method was not suitable for supercritical flows, so this author was not successful in developing a fully dynamic model.

Further optimization of the computer code developed for this research should be researched. Currently the simulation time is approximately 30 minutes a 2,000-foot pipeline simulating 60-seconds. The Algebraic Method (Wylie 1993) also known as the Reach Back Method may be appropriate. The method could be applied by using short reaches in the free surface portion and the transition portion where detail is needed. Then the method would reach back a number of time steps in the full pipe part of the system where the interior point detail is not needed. This could enable small time steps, but save computational effort by eliminating a several of unnecessary interior points. In addition, simulation of the movement of the free-surface pressurized transition could be modeled as an inertial volume (or a large surge tank) at a fixed location for the simulation but would represent movement of the transition. Similar to the current research, the transition would move based on the transients generated from downstream. This would allow longer pipe reaches and reduced simulation time

Future research could include gathering of field data on the movement of free-surface/pressurized transitions to validate the model. Within the past several months, fiber optic cables have been installed in some of the large transmission pipelines in San Diego County. These fiber optic cables capture acoustic data from the pipeline for the main purpose of determining if any structural damage is occurring. However, the acoustic information may be used to determine the approximate location and movement of the free-surface/pressurized flow interface. The author is able to view the data and to correlate the location of acoustic noise with the location of a hydraulic jump, however the data cannot be exported. It may be possible to capture this data in the future for analysis.

APPENDICES

APPENDIX A

COMPUTER PROGRAM CODE

Module: HT 0 Steady State

```
Attribute VB_Name = "HT_0_Steady_State"
' Calculates the Pipeline Profile Based on the Input Parameters
Sub Calc_x()

    Dim count As Integer
    Dim cell1, cell2, rng As Range

' Get Variables from the Spreadsheet
    Length = Worksheets("Steady_State").Range("L")
    dx = Worksheets("Steady_State").Range("dx")
    Slope = Worksheets("Steady_State").Range("S")
    diameter = Worksheets("Steady_State").Range("diam_ft")

'Initialize Values and Clear Spreasheet Values where new values will
write
    count = 0

   'Clear Previous Values
    Worksheets("SS_Output").Cells.ClearContents

   'Insert Column Lables
    Worksheets("SS_Output").Cells(1, 1).Value = "x (feet)"
    Worksheets("SS_Output").Cells(1, 2).Value = "Pipe Invert (feet)"
    Worksheets("SS_Output").Cells(1, 3).Value = "Top of Pipe (feet)"

    'Calculate Pipeline Profile Values in the Spreadsheet
    For I = 2 To (2 + (Length / dx))

        Worksheets("SS_Output").Cells(I, "A").Value = Length - (count *
dx)
        Worksheets("SS_Output").Cells(I, "B").Value =
Worksheets("SS_Output").Cells(I, "B") + (count * dx * Slope)
        Worksheets("SS_Output").Cells(I, "C").Value =
Worksheets("SS_Output").Cells(I, "B") + (diameter)

        count = count + 1

    Next I

End Sub
' Calculates the Steady State Hydraulic Grade Elevation and Water
Surface Elevation
Sub HGL()

    Dim HGL, count, Row, x, fy, yx, Seq_Depth As Double
    Dim a_cos, CD As Double
    Dim ds_valve_loc, us_res_loc, E As Integer

' Get Variables from the Spreadsheet
    DS_WS = Worksheets("Steady_State").Range("DS_WSEL")
    mn = Worksheets("Steady_State").Range("mn")
```

```
    f = Worksheets("Steady_State").Range("D_W_f")
    dx = Worksheets("Steady_State").Range("dx")
    Q = Worksheets("Steady_State").Range("Q")
    Diam = Worksheets("Steady_State").Range("diam_ft")
    Length = Worksheets("Steady_State").Range("L")
    depth1 = Worksheets("Steady_State").Range("depth1")
    delta_y = Worksheets("Steady_State").Range("delta_y_jump")
    S = Worksheets("Steady_State").Range("S")
    g = Worksheets("Steady_State").Range("g")
    nd = Worksheets("Steady_State").Range("nd")
    A_p = Worksheets("Steady_State").Range("A_P")
    jump_1 = Worksheets("Steady_State").Range("jump_1")
    L = Worksheets("Steady_State").Range("L")
    Seq_Depth = Worksheets("Steady_State").Range("Seq_Depth")
    Ho = Worksheets("Steady_State").Range("Ho")

' Initialize Values
    count = 1
    Row = 2
    HGL = DS_WS
    us_res_loc = L / dx
    ds_res_loc = 1

    Worksheets("SS_Output").Cells(2, 4).Value = HGL
    If HGL < Diam Then
        Worksheets("SS_Output").Cells(2, 6).Value = "-"
        Else: Worksheets("SS_Output").Cells(2, 6).Value = Q / A_p
    End If

'Insert Column Lables
    Worksheets("SS_Output").Cells(1, 4).Value = "HGL or WS El. (feet)"
    Worksheets("SS_Output").Cells(1, 5).Value = "Depth (feet)"
    Worksheets("SS_Output").Cells(1, 6).Value = "Velocity
(feet/second)"

    If DS_WS <= Diam Then
        yi = DS_WS
        Worksheets("SS_Output").Cells(Row, 4).Value = yi
        GoTo 200
    End If

' 1. First Calculate the Pressurized Flow Steady State Hydraulics
' Stop When HGL is at the Top of the Pipe
    Do

    Row = Row + 1

    HGL = HGL + ((f * (dx / Diam) * ((Q ^ 2) / (A_p ^ 2 * 2 * g))))

    yi = HGL - Worksheets("SS_Output").Cells(Row, 2)

    If yi < Seq_Depth Then
        Row = Row - 1
        GoTo 200
```

```
    End If

    Worksheets("SS_Output").Cells(Row, 4).Value = HGL
    Worksheets("SS_Output").Cells(Row, 6).Value = Q / (A_p)
    If count = us_res_loc Then
Worksheets("Steady_State").Range("US_WSEL").Value = HGL

    count = count + 1

    If count = 1 + (Length / dx) Then GoTo 130

    Loop Until HGL <= Worksheets("SS_Output").Cells(Row, 3)

' 2. Water Surface Profile of the Hydraulic Jump - Simply a Numerical
calculation based on the lenght of the Jump
' Stop when sequent depth of jump is reached
200 Do

    Row = Row + 1
    count = count + 1
    yi = yi - delta_y

    HGL = Worksheets("SS_Output").Cells(Row, 2) + yi

    If yi < 0.01 Then
        yi = nd
        HGL = yi + Worksheets("SS_Output").Cells(Row, 2)
    End If

    Worksheets("SS_Output").Cells(Row, 4).Value = HGL
    If count = us_res_loc Then
        Worksheets("SS_Output").Cells(Row, 5).Value = "U/S Res"
        Else: Worksheets("SS_Output").Cells(Row, 5).Value = yi
    End If

    Worksheets("SS_Output").Cells(Row, 6).Value = "Hydraulic Jump"
    If count = us_res_loc Then
Worksheets("Steady_State").Range("US_WSEL").Value = HGL

    If count = 2 + (Length / dx) Then GoTo 130

    Loop Until yi <= depth1

    GoTo 310

' 3. Finally use the Single Step Method with the Improved Euler
Numerical Method
' To caclulate the Water Surface Profile for Supercritical Free-Surface
Flow

310 E = Row
    Row = 2 + (Length / dx)
    CD = Worksheets("Steady_State").Range("Crit_D")
    yi = CD
```

```
    HGL = yi + Worksheets("SS_Output").Cells(Row, 2)
    Worksheets("Steady_State").Range("US_WSEL").Value = HGL
    Worksheets("SS_Output").Cells(Row, 4).Value = HGL
    Worksheets("SS_Output").Cells(Row, 5).Value =
Worksheets("SS_Output").Cells(Row, 4) -
Worksheets("SS_Output").Cells(Row, 2)
    yi = CD - (dx / 10)
    If yi < 1 Then yi = 1

    For count = 1 + (Length / dx) To E Step -1

    Row = Row - 1

    ' Get Theta - VB cannot calculate arc-cosine
        x = 1 - 2 * yi / Diam
        a_cos = Atn(-x / Sqr(-x * x + 1)) + 2 * Atn(1)
        t = 2 * a_cos

    ' Use Theta to Get A,R and B
        A = (1 / 8) * (t - Sin(t)) * (Diam ^ 2)
        R = (1 / 4) * (1 - (Sin(t) / t)) * (Diam)
        b = Diam * (Sin(0.5 * t))

    'Calculate the Slope of Friction and F(x,y)
        Sf = ((mn ^ 2) * (Q ^ 2)) / (2.2 * (A ^ 2) * (R ^ (2 / 3)))
        fy = ((-S + Sf) / ((1 - ((Q ^ 2) * b) / (g * A ^ 3))))

    ' Euler Method
        yi1_star = yi - (fy * dx)

        ' Get F(x,yi1_star)
            x = 1 - 2 * yi1_star / Diam
            a_cos = Atn(-x / (-x * x + 1) ^ (0.5)) + 2 * Atn(1)
            t = 2 * a_cos

            A = (1 / 8) * (t - Sin(t)) * (Diam ^ 2)
            R = (1 / 4) * (1 - (Sin(t) / t)) * (Diam)
            b = Diam * (Sin(0.5 * t))

            Sf2 = ((mn ^ 2) * (Q ^ 2)) / (2.2 * (A ^ 2) * (R ^ (2 /
3)))
            fy2 = ((-S + Sf) / ((1 - ((Q ^ 2) * b) / (g * A ^ 3))))

    'Improved Euler Method
        yi1 = yi - 0.5 * ((fy + fy2) * dx)

    yi = yi1

    HGL = yi1 + Worksheets("SS_Output").Cells(Row, 2)
    Worksheets("SS_Output").Cells(Row, 4).Value = HGL
    Worksheets("SS_Output").Cells(Row, 5).Value =
Worksheets("SS_Output").Cells(Row, 4) -
Worksheets("SS_Output").Cells(Row, 2)
    Worksheets("SS_Output").Cells(Row, 6).Value = Q / A
```

```
  Next count
130

End Sub

Function ndepth()

    Dim A, R, Fyn As Double
    Dim Acos, x As Double


    Diam = Worksheets("Steady_State").Range("diam_ft")
    Q = Worksheets("Steady_State").Range("Q")
    mn = Worksheets("Steady_State").Range("mn")
    Co = Worksheets("Steady_State").Range("Co")
    S = Worksheets("Steady_State").Range("S")

    If S = 0 Then
        Cells(18, "K").Value = "-"
        GoTo 100
    End If

    yn = 0.1
    Fyn = 200

    Do Until Fyn > -0.01 And Fyn < 0.01
        x = 1 - 2 * yn / Diam
        Acos = Atn(-x / Sqr(-x * x + 1)) + 2 * Atn(1)
        t = 2 * Acos

        A = (1 / 8) * (t - Sin(t)) * (Diam ^ 2)
        R = (1 / 4) * (1 - (Sin(t) / t)) * (Diam)
        b = Diam * (Sin(0.5 * t))

        Fyn = (A * R ^ (2 / 3)) - ((mn * Q) / (Co * (S ^ (0.5))))
        yn = yn + 0.001
        If yn > 0.95 * Diam Then
            MsgBox "Flow Too High for Open Channel"
            Cells(18, "K").Value = "-"
            GoTo 100
        End If

    Loop

    Cells(18, "K").Value = yn
    Range("nd_V").Value = Q / A
    Range("nd_A").Value = A
    Range("nd_B").Value = b

100 End Function

Function cdepth()
```

```
    Dim A, R, D, Z As Double

    Diam = Worksheets("Steady_State").Range("diam_ft")
    Q = Worksheets("Steady_State").Range("Q")
    S = Worksheets("Steady_State").Range("S")
    g = Worksheets("Steady_State").Range("g")

    yc = 0.001
    Z = 100

    Do Until Z >= -0.01 And Z < 0.01
        x = 1 - 2 * yc / Diam
        Acos = Atn(-x / Sqr(-x * x + 1)) + 2 * Atn(1)
        t = 2 * Acos

        A = (1 / 8) * (t - Sin(t)) * (Diam ^ 2)
        R = (1 / 4) * (1 - (Sin(t) / t)) * (Diam)
        D = ((t - Sin(t)) / (Sin(0.5 * t)) * (Diam / 8))

        Z = (A * (D ^ (0.5))) - ((Q / ((cos(S)) ^ (0.5)))) / (g ^
(0.5))
        yc = yc + 0.001

'   Loop

    Cells(19, "K").Value = yc

End Function
```

Module: HT 1 InitialConditions

```
Attribute VB_Name = "HT_1_InitialConditions"

Sub Initial_Conditions()

    Dim R, c, Row, stp, IBC_Loc As Integer
    Dim cell1, cell2, rng As Range

'Initialize Varibles
    Row = 2
    c = 2
    R = 3

    dt = Worksheets("Hydraulic_Transient_Input").Range("dt")
    dx = Worksheets("Steady_State").Range("dx")
    L = Worksheets("Steady_State").Range("L")
    S = Worksheets("Steady_State").Range("S")
    Diam = Worksheets("Steady_State").Range("diam_ft")

'Clear Previous Values
    Worksheets("HT_Output").Cells.Clear

'Set marker and inital time
    Worksheets("HT_Output").Cells(1, 1).Value = "t columns,x rows"
    Worksheets("HT_Output").Cells(2, 1).Value = "Pipe Invert"
    Worksheets("HT_Output").Cells(3, 1).Value = 0
    Worksheets("HT_Output").Cells(4, 1).Value = 0

' Set x values
    For c = 2 + (2 * (L / dx)) To 2 Step -2
        Worksheets("HT_Output").Cells(1, c).Value =
Worksheets("SS_Output").Cells(Row, 1)
        Worksheets("HT_Output").Cells(2, c).Value =
Worksheets("SS_Output").Cells(Row, 2)
        If Not c = 2 Then Worksheets("HT_Output").Cells(2, c - 1).Value
= Worksheets("HT_Output").Cells(2, c).Value + (S * (dx / 2))
        If Not c = 2 + (2 * (L / dx)) Then
Worksheets("HT_Output").Cells(1, c + 1).Value =
Worksheets("SS_Output").Cells(Row, 1) + (dx / 2)

        Row = Row + 1

    Next c

    Row = 2
    IBC_Loc = 0

' Set Initial Conditions based on Steady State Output
    For c = 2 + (2 * (L / dx)) To 2 Step -2
        Worksheets("HT_Output").Cells(3, c).Value =
Worksheets("SS_Output").Cells(Row, 4)
        Worksheets("HT_Output").Cells(4, c).Value =
Worksheets("Steady_State").Range("Q")
```

```
        Worksheets("HT_Output_ReportH").Cells(5, 1 + (c / 2)).Value =
Worksheets("SS_Output").Cells(Row, 4)

        If Worksheets("HT_Output").Cells(3, c) <
Worksheets("HT_Output").Cells(2, c) + Diam And IBC_Loc = 0 Then
            IBC_Loc = c + 2
            'dx_w = -(Worksheets("HT_Output").Cells(3, c + 2) -
(Worksheets("HT_Output").Cells(2, c) + Diam)) * S

Worksheets("Hydraulic_Transient_Input").Range("IC_Loc").Value = IBC_Loc
            Worksheets("HT_Output").Cells(3, c + 2).Interior.Color =
RGB(255, 255, 0)
            Worksheets("HT_Output").Cells(4, c + 2).Interior.Color =
RGB(255, 255, 0)
            Worksheets("Hydraulic_Transient_Input").Range("dx_w").Value
= 0
        End If

        Row = Row + 1

    Next c

    For c = 1 + (2 * (L / dx)) To 3 Step -2
        Worksheets("HT_Output").Cells(3, c).Value = 0.5 *
((Worksheets("HT_Output").Cells(3, c - 1)) +
(Worksheets("HT_Output").Cells(3, c + 1)))
        Worksheets("HT_Output").Cells(4, c).Value =
Worksheets("Steady_State").Range("Q")

    Next c

    Worksheets("Hydraulic_Transient_Input").Range("IC_Loc").Value =
IBC_Loc

End Sub
```

Module: HT 2 Routine

```
Attribute VB_Name = "HT_2_Routine"
' Runs the A Hydraulic Transient Model for Combined Free Surface
Pressurized Flow Pipelines
Sub CFSPFP()

    Dim L, dx, dt, t As Double
    Dim dz, tau As Double
    Dim Row, Col, IBC_Loc As Integer
    Dim Display_Row, Contents_Row, DLast_Cell, DFirst_Cell, CLast_Cell,
CFirst_Cell As Range
    Dim Row1, Col1 As String

' Initialize Values
    dt = Worksheets("Hydraulic_Transient_Input").Range("dt")
    total_time =
Worksheets("Hydraulic_Transient_Input").Range("total_time")
    dx = Worksheets("Steady_State").Range("dx")
    L = Worksheets("Steady_State").Range("L")
    S = Worksheets("Steady_State").Range("S")
    IBC_Loc = Worksheets("Hydraulic_Transient_Input").Range("IC_Loc")

    Diam = Worksheets("Steady_State").Range("diam_ft")

    t = 0

    Set DLast_Cell = Worksheets("HT_Output_ReportH").Cells(2, 2 + (L /
dx))
    Set DFirst_Cell = Worksheets("HT_Output_ReportH").Cells(2, 2)
    Set Display_Row =
Worksheets("HT_Output_ReportH").Range(DFirst_Cell, DLast_Cell)

For Row = 5 To 5 + (4 * (total_time / dt)) Step 2

'Update time
    Worksheets("HT_Output").Cells(Row, 1).Value = t + (dt / 2)
    Worksheets("HT_Output").Cells(Row + 1, 1).Value = t + (dt / 2)

'Determine if the calculation is an intermediate time step
    If ((Row - 1) / 4) = Int((Row - 1) / 4) Then GoTo 100 Else GoTo 200

        'Calculations for intermediate time steps (no boundary
conditions)
100     For Col = 3 To 1 + (2 * (L / dx)) Step 2

        If Col < IBC_Loc And IBC_Loc <> 0 Then
            Call FS_SC(Row, Col, IBC_Loc, dz)
            GoTo 300
        End If

        Call MOC(Row, Col, Flag, IBC_Loc, RTS)
```

```
300     Next Col

        If IBC_Loc <> 0 Then Call Internal_BC(Row, dz)

        GoTo 900

        'Calculations for reported time steps
200     If ((1 + Row)) = Int((1 + Row)) Then

            'Set Graph Diplay information
            If Worksheets("Hydraulic_Transient_Input").Range("SR") =
"Yes" Then
                Set CFirst_Cell =
Worksheets("HT_Output_ReportH").Cells(2 + ((Row + 1) / 4), 2)
                Set CLast_Cell =
Worksheets("HT_Output_ReportH").Cells(2 + ((Row + 1) / 4), 2 + (L /
dx))
                Set Contents_Row =
Worksheets("HT_Output_ReportH").Range(CFirst_Cell, CLast_Cell)
                Contents_Row.Copy Display_Row

                'Set min and max display rows
                For c = 2 + (L / dx) To 2 Step -1
                    last = (2 + ((Row + 1) / 4) + 1)
                    Col1 = "R5C" & c
                    Row1 = "R" & last & "C" & c
                    Worksheets("HT_Output_ReportH").Cells(3,
c).FormulaR1C1 = "=MAX(" & Col1 & ":" & Row1 & ")"
                    Col1 = "R5C" & c
                    Row1 = "R" & last & "C" & c
                    Worksheets("HT_Output_ReportH").Cells(4,
c).FormulaR1C1 = "=MIN(" & Col1 & ":" & Row1 & ")"
                Next c
                If
Worksheets("Hydraulic_Transient_Input").Range("Delay") = "Yes" Then
                    Application.Wait Format(Now +
TimeValue("00:00:01"), "hh:mm:ss")
                End If
            End If

        End If

        Call Boundary_Conditions(Row, IBC_Loc, dz, Flag, tau)

        For Col = 4 To (1 + (2 * (L / dx))) Step 2

        If Col < IBC_Loc And IBC_Loc <> 0 Then
            Call FS_SC(Row, Col, IBC_Loc, dz)
            GoTo 400
        End If

        If Col = IBC_Loc Then Col = Col + 2
        RTS = 1
        Call MOC(Row, Col, Flag, IBC_Loc, RTS)
```

```
        RTS = 0

400     Worksheets("HT_Output_ReportH").Cells(4 + ((Row + 1) / 4), 1 +
(Col / 2)).Value = Worksheets("HT_Output").Cells(Row, Col)
        Worksheets("HT_Output_ReportH").Cells(2, 1).Value = (t - (dt))
+ (dt / 2)
        Worksheets("HT_Output_ReportH").Cells(4 + ((Row + 1) / 4), 5 +
(L / dx)).Value = tau

        Next Col

        GoTo 900

900     t = t + (dt / 2)

Next Row

End Sub
```

Module: HT 3 PF Engine MOC

```
Attribute VB_Name = "HT_3_PF_Engine_MOC"
' Runs the Method of Characteristics for Pressurized Flow
Sub MOC(Row, Col, Flag, IBC_Loc, RTS)

    Dim Cp, Cn, Hp, Qp, Qa, Ha, Qb, Hb, Cv As Double

    Diam = Worksheets("Steady_State").Range("diam_ft")

'Get B- Pipeline Characteristic Impedance and R - Pipeline Resistance
Coefficent from Input Information
    Ca = Worksheets("Hydraulic_Transient_Input").Range("B")
    R = Worksheets("Hydraulic_Transient_Input").Range("R_coef")
    nd = Worksheets("Steady_State").Range("nd")

    Qa = Worksheets("HT_Output").Cells(Row - 1, Col - 1)
    Ha = Worksheets("HT_Output").Cells(Row - 2, Col - 1)
    Qb = Worksheets("HT_Output").Cells(Row - 1, Col + 1)
    Hb = Worksheets("HT_Output").Cells(Row - 2, Col + 1)

    Cp = Qa + (Ca * Ha) - R * Qa * (Abs(Qa))
    Cn = Qb - (Ca * Hb) - R * Qb * (Abs(Qb))

    Qp = 0.5 * (Cp + Cn)
    Hp = (Qp - Cn) / Ca

    If Flag = 1 Then
        Cn = Qb - (Ca * Hb) - R * Qb * (Abs(Qb))

        Hp = Worksheets("HT_Output").Cells(Row - 4, Col) + (dz)
        Qp = Cn + (Ca * Hp)

        Flag = 0
    End If

    Worksheets("HT_Output").Cells(Row, Col).Value = Hp
    Worksheets("HT_Output").Cells(Row + 1, Col).Value = Qp

End Sub
```

Module: HT 4 FS Engine

```
Attribute VB_Name = "HT_4_FS_Engine"
'Calculates the Water Surface Profile for Supercritical Free Surface
Flow
'Assumes upstream conditions are constant - no transients in Free
Surface Portion
Sub FS_SC(Row, Col, IBC_Loc, dz)

    Dim Hp, Qp As Double

        Initial_IBC_Loc =
Worksheets("Hydraulic_Transient_Input").Range("IC_Loc")

        'Use normal depth when transient is below initial free-
surface/pressurized boundary
        If IBC_Loc > Initial_IBC_Loc + 1 Then
            nd = Worksheets("Steady_State").Range("nd").Value
            Qp = Worksheets("HT_Output").Cells(4, Col)
            Hp = Worksheets("HT_Output").Cells(2, Col) + nd
            GoTo 100
        End If

        'Use Initial Conditions
        Qp = Worksheets("HT_Output").Cells(4, Col)
        Hp = Worksheets("HT_Output").Cells(3, Col)

100     Worksheets("HT_Output").Cells(Row, Col).Value = Hp
        Worksheets("HT_Output").Cells(Row + 1, Col).Value = Qp

End Sub
```

Module: HT 5 BC

```
Attribute VB_Name = "HT_5_BC"


Sub Boundary_Conditions(Row, IBC_Loc, dz, Flag, tau)

    Dim Upstream_BC, Downstream_BC, Internal_BC_1, Internal_BC_2 As
Characters
    Dim tau_i, tau_f, ds_bc_valve_move, tc, Cv_init, Cv, t, wm, dx As
Double

    Upstream_BC = Worksheets("Steady_State").Range("us_bc")
    Downstream_BC = Worksheets("Steady_State").Range("ds_bc")
    Diam = Worksheets("Steady_State").Range("diam_ft")
    Q_I = Worksheets("Steady_State").Range("Q")
    S = Worksheets("Steady_State").Range("S")
    Ca = Worksheets("Hydraulic_Transient_Input").Range("B")
    R = Worksheets("Hydraulic_Transient_Input").Range("R_coef")
    nd = Worksheets("Steady_State").Range("nd")
    Ho = Worksheets("Steady_State").Range("Ho")

    tau_i = Worksheets("Hydraulic_Transient_Input").Range("tau_i")
    tau_f = Worksheets("Hydraulic_Transient_Input").Range("tau_final")
    ds_bc_valve_move =
Worksheets("Hydraulic_Transient_Input").Range("ds_bc_valvestart")
    tc = Worksheets("Hydraulic_Transient_Input").Range("tc")
    ds_bc_Cv_init =
Worksheets("Steady_State").Range("ds_bc_valve_cv_init")
    dx = Worksheets("Steady_State").Range("dx")
    L = Worksheets("Steady_State").Range("L")
    dt = Worksheets("Hydraulic_Transient_Input").Range("dt")

    t = Worksheets("HT_Output").Cells(Row, 1)

    Col = 2

'Downstream Valve
    If Downstream_BC = "Valve" Then
        If t > ds_bc_valve_move And t < tc Then
            tau = tau_i - ((tau_i - tau_f) * ((t / tc)) ^ (0.75))
        ElseIf t < ds_bc Then
            tau = tau_i
        ElseIf t >= tc Then
            tau = tau_f
        End If

    Cv = (tau ^ 2) * ds_bc_Cv_init
    Qa = Worksheets("HT_Output").Cells(Row - 1, 1 + (2 * (L / dx)))
    Ha = Worksheets("HT_Output").Cells(Row - 2, 1 + (2 * (L / dx)))
    Cp = Qa + (Ca * Ha) - R * Qa * (Abs(Qa))

    Qp = 0.5 * (-Cv + (Cv ^ 2 + 4 * Cp * Cv) ^ (0.5))
```

```
    Hp = (Qp - Cp) / -Ca

    Worksheets("HT_Output").Cells(Row, 2 + (2 * (L / dx))).Value = Hp
    Worksheets("HT_Output").Cells(Row + 1, 2 + (2 * (L / dx))).Value =
Qp
    Worksheets("HT_Output_ReportH").Cells(((Row + 2) / 4) + 4, 2 + (L /
dx)).Value = Hp

'For Downstream Reservoir
    Else

        Qa = Worksheets("HT_Output").Cells(Row - 1, 1 + (2 * (L / dx)))
        Ha = Worksheets("HT_Output").Cells(Row - 2, 1 + (2 * (L / dx)))

        Cp = Qa + (Ca * Ha) - R * Qa * (Abs(Qa))

        Hres = Worksheets("Steady_State").Range("dsbc_res_wsel")

        Qp = Cp - Ca * Hres

        Hp = (Qp - Cp) / -Ca

        Worksheets("HT_Output").Cells(Row, 2 + (2 * (L / dx))).Value =
Hp
        Worksheets("HT_Output").Cells(Row + 1, 2 + (2 * (L /
dx))).Value = Qp
        Worksheets("HT_Output_ReportH").Cells(((Row + 2) / 4) + 4, 2 +
(L / dx)).Value = Hp

    End If

'Upstream Boundary Condition - Reservoir in Supercritical Flow

    If Upstream_BC = "Supercritical Upstream BC" Then
        Worksheets("HT_Output").Cells(Row, 2).Value =
Worksheets("Steady_State").Range("US_WSEL")
        Worksheets("HT_Output").Cells(Row + 1, 2).Value =
Worksheets("Steady_State").Range("Q")
        Worksheets("HT_Output_ReportH").Cells(((Row + 2) / 4) + 4,
2).Value = Worksheets("Steady_State").Range("US_WSEL")
    End If

'Internal Boundary Condition - Fixed
    If IBC_Loc <> 0 Then
            Qb = Worksheets("HT_Output").Cells(Row - 1, IBC_Loc + 1)
            Hb = Worksheets("HT_Output").Cells(Row - 2, IBC_Loc + 1)
        Else
            GoTo 100
    End If

    Cn = Qb - (Ca * Hb) - R * Qb * (Abs(Qb))
    Hres = Worksheets("HT_Output").Cells(Row - 4, IBC_Loc) + dz
    Qp = Cn + (Ca * Hres)
    Hp = (Qp - Cn) / Ca
```

```
    If Hp >= Worksheets("HT_Output").Cells(2, IBC_Loc - 2) + Diam Then
        IBC_Loc = IBC_Loc - 2
        Worksheets("HT_Output").Cells(Row, IBC_Loc - 2).Value =
Worksheets("HT_Output").Cells(2, IBC_Loc - 2) + Diam
        Flag = 1
    End If
    If Hp < Worksheets("HT_Output").Cells(2, IBC_Loc) + nd Then
        Hp = Worksheets("HT_Output").Cells(2, IBC_Loc) + nd
        IBC_Loc = IBC_Loc + 2
        Flag = 1
    End If

    wm = (((S * dx) - ((Worksheets("HT_Output").Cells(2, IBC_Loc - 2) +
Diam) - Hp)) / (S * dx)) * dx
    Worksheets("HT_Output_ReportH").Cells(4 + ((Row + 1) / 4), 4 + (L /
dx)).Value = ((IBC_Loc - 2) * (dx / 2)) - wm


    Worksheets("HT_Output").Cells(Row, IBC_Loc).Value = Hp
    Worksheets("HT_Output").Cells(Row + 1, IBC_Loc).Value = Qp
    Worksheets("HT_Output").Cells(Row, IBC_Loc).Interior.Color =
RGB(255, 255, 0)
    Worksheets("HT_Output").Cells(Row + 1, IBC_Loc).Interior.Color =
RGB(255, 255, 0)
    Worksheets("HT_Output_ReportH").Cells(((Row + 2) / 4) + 4, 1 +
(IBC_Loc / 2)).Value = Hp

    'Upstream Boundary Condition
100   If Upstream_BC = "Reservoir" Then

        Qb = Worksheets("HT_Output").Cells(Row - 1, Col + 1)
        Hb = Worksheets("HT_Output").Cells(Row - 2, Col + 1)

        Cn = Qb - (Ca * Hb) - R * Qb * (Abs(Qb))

        Hres = Worksheets("Steady_State").Range("US_WSEL")

        Qp = Cn + (Ca * Hres)

        Hp = (Qp - Cn) / Ca

        Worksheets("HT_Output").Cells(Row, 2).Value = Hp
        Worksheets("HT_Output").Cells(Row + 1, 2).Value = Qp
        Worksheets("HT_Output_ReportH").Cells(((Row + 2) / 4) + 4,
2).Value = Hp

    End If

End Sub


Sub Internal_BC(Row, dz)
```

```
        Dim x, dt, dx, theta As Double

        theta = Worksheets("Steady_State").Range("theta")
        Diam = Worksheets("Steady_State").Range("diam_ft")
        S = Worksheets("Steady_State").Range("S")
        dt = Worksheets("Hydraulic_Transient_Input").Range("dt")
        dx = Worksheets("Steady_State").Range("dx")
        L = Worksheets("Steady_State").Range("L")
        Q_I = Worksheets("Steady_State").Range("Q")
        theta = Worksheets("Steady_State").Range("theta")

        Qa = Q_I
        Qv = Worksheets("HT_Output").Cells(Row - 1, 2 + (2 * (L / dx)))
        SA_p = 3.14 * (Diam / 2) * (0.5 * Diam * (1 / Sin(theta)))

        dz = (1 / (SA_p)) * (Qa - Qv) * dt

End Sub
```

Module: HT 6 Output

```
Attribute VB_Name = "HT_6_Output"

Sub OutputHT_Hx()
    Dim R, c, Row, stp As Integer
    Dim cell1, cell2, rng As Range
    Dim last As Integer

'Clear Previous Values
    Worksheets("HT_Output_ReportH").Cells.Clear

'Initialize Varibles
    Row = 2
    c = 2
    t = 0

    dt = Worksheets("Hydraulic_Transient_Input").Range("dt")
    dx = Worksheets("Steady_State").Range("dx")
    L = Worksheets("Steady_State").Range("L")
    total_t =
Worksheets("Hydraulic_Transient_Input").Range("total_time")

' Set x values
    For c = 2 + (L / dx) To 2 Step -1
        Worksheets("HT_Output_ReportH").Cells(1, c).Value =
Worksheets("SS_Output").Cells(Row, 1)

        Row = Row + 1

    Next c

' Set t values
Worksheets("HT_Output_ReportH").Cells(5, 1).Value = 0
Worksheets("HT_Output_ReportH").Cells(3, 1).Value = "Max"
Worksheets("HT_Output_ReportH").Cells(4, 1).Value = "Min"
Worksheets("HT_Output_ReportH").Cells(1, 4 + (L / dx)).Value =
"IBC_Location"

    For Row = 6 To 6 + (total_t / dt)
        t = t + dt
        Worksheets("HT_Output_ReportH").Cells(Row, 1).Value = t

    Next Row

r1 = 3
c1 = 0

End Sub
```

APPENDIX B

COMPUTER PROGRAM INTERFACE

Steady State Computer Program – User Interface

Combined Free-Surface Pressurized Flow Pipelines: Steady State Input

Input Data:

Pipe Diameter=	72	inches =	6	feet
Pipe Length=	1000	feet		
Pipe Slope=	0.25			
Initial Flow Rate =	100	cfs		
Manning Friction Factor (n) =	0.012			
Downstream Reservoir W.S. El. Upstream of Valve=	100.00	feet		
Numer of Sections for Computations =	40			
dx =	25			

Go To Steady State Output | Pipeline Profile | Go To Hydraulic Transient Input Page

Boundary Condition/Pipeline Features Data:

Downstream Boundary Condition

Downstream Boundary Condition =	Valve
Downstream Valve Type =	Generic
Initial Headloss =	100
Initial Cv =	502.0149
Dowstream Reservoir W.S. El. =	100

Upstream Boundary Condition

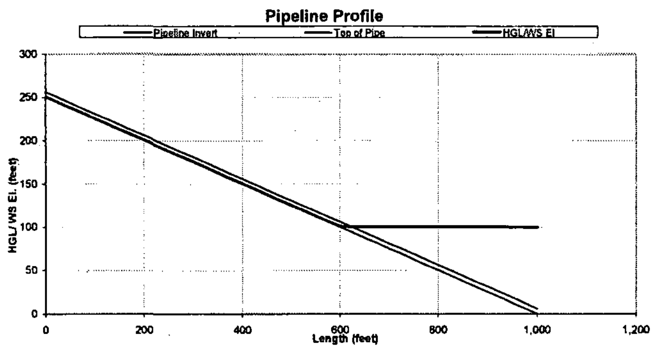
Upstream Boundary Condition =	[illegible] upstream BC
Upstream Reservoir W.S. El =	250.75496 feet

Hydraulic Jump - Calculated Data

Pressurized Area =	28.26	square feet	1.5
Pressurized Velocity =	3.54	feet/second	
Pressurized Conduit Fr =	0.25		
y_1 -sequent depth (at jump) =	0.70	feet	
Free-Surface Area =	1.83	square feet	
Free-Surface Velocity =	54.58	feet/second	
Free-Surface Fr =	11.52		
jump length =	68.20	feet	
theta =	1.391		
jump_dy =	1.944	feet	

Free-Surface - Calculated Data

Normal Depth =	0.85	feet
Critical Depth =	2.71	feet
C_o =	1.49	
Gravity =	32.2	ft/s2
Normal Depth Velocity =	40.78	fps
A=	2.45	
B=	4.19	
c (Celerity) =	4.34	



Hydraulic Transient Computer Program – User Interface

Combined Free-Surface Pressurized Flow Pipelines: Hydraulic Transient Data Input

Input Data:

Pipe Material = [illegible]
Pipe Youngs Modulus(E) = [illegible] lb/ft²
Pipe Steel Thickness = [illegible] in
Fluid Density = [illegible] slugs/ft³
Bulk Modulus (K) = [illegible] lb/ft²
Type of Pipe to determine Psi = [illegible] Conduit - anchored throghout its length
Poisson's Ratio = [illegible]
Darcy Wiesbac Friction Factor = [illegible]

Simulation Time = [illegible] seconds
Animated Graph (Speed) = [illegible]
Animation Delay = [illegible]

Hydraulic Transient Model - Calculated Data

Pipe Diameter= 72 inches = 6 feet 28.31 square feet
Psi = 10 Thin-Walled Elastic Conduit - anchored throghout its length
a = 4,577 feet/second
length = 1,000 feet
Pipe Slope= 0.250
Initial Flow Rate = 100 cfs
Downstream Reservoir W.S. EL = 100 feet
Numer of Sections for Computations = 40
Gravity = 32.2 ft/s2
Pipeline Characteristic Impedance (Ca) = 0.199197274
Pipeline Resistance Coefficent (R) = 2.943E-07

dx/2= 12.50
delta t = 0.00546 seconds
Total Time Steps = 1830

0
Time Step = 9.993690491 seconds

Full Output - Method of Characteristics | Head vs. Time Output | Transient Plot | DS Location Plot

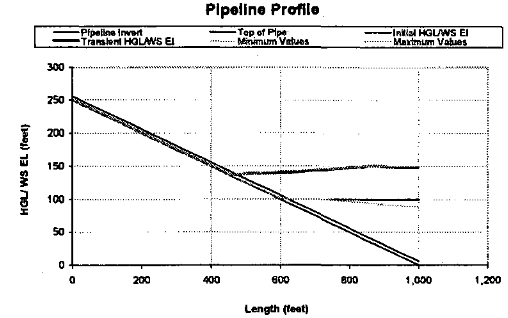
Boundary Condition/Pipeline Features Data:

Downstream Boundary Condition
Downstream Boundary Condition = Valve
Downstream Valve Type = Generic
K at 100 percent open = 0.4
Initial Headloss = 100
Initial Cv = 502.0149025

Starting Time for Movement [illegible]
Time of closure [illegible] seconds
initial tau [illegible]
final tau [illegible]

Upstream Boundary Condition
Upstream Boundary Condition = Supercritical Upstream BC
Upstream Reservoir W.S. El = 250.75 feet

Pipeline Profile



Hydraulic Transient – Characteristic Grid Method Output

	1	2	3	4	5	6	7	8	9	10	11	12
1	t columns,x rows	0	100	200	300	400	500	600	700	800	900	1000
2	Pipe Invert	250	225	200	175	150	125	100	75	50	25	0
3	0	250.773	225.76	200.74	175.77	150.79	125.76	100.72	100.41	100.1	100.05	100
4	0	100	100	100	100	100	100	100	100	100	100	100
5	0.023390733		225.76		175.77		125.76		100.41		100.05	
6	0.023390733		100		100		100		100		100.01	
7	0.046781465	250.773		200.74		150.79		100.72		100.1		284.5
8	0.046781465	105.332		100		100		100		100.01		60.67
9	0.070172198		225.76		175.77		125.76		100.41		284.55	
10	0.070172198		100		100		100		100		60.678	
11	0.09356293	250.773		200.74		150.79		100.72		100.16		284.54
12	0.09356293	105.332		100		100		100		21.357		60.678
13	0.116953663		225.76		175.77		125.76		100.41		100.16	
14	0.116953663		100		100		100		100		21.357	
15	0.140344395	250.773		200.74		150.79		100.72		100.23		100.15
16	0.140344395	105.332		100		100		100		21.372		21.358
17	0.163735128		225.76		175.77		125.76		100.41		100.22	
18	0.163735128		100		100		100		100		21.372	
19	0.187125861	250.773		200.74		150.79		100.72		100.36		100.22
20	0.187125861	105.332		100		100		100		21.401		21.372
21	0.210516593		225.76		175.77		125.76		100.41		100.36	
22	0.210516593		100		100		100		100		21.401	
23	0.233907326	250.773		200.74		150.79		100.72		100.49		100.35
24	0.233907326	105.332		100		100		100		21.428		21.401
25	0.257298058		225.76		175.77		125.76		100.41		100.49	
26	0.257298058		100		100		100		100		21.428	
27	0.280688791	250.773		200.74		150.79		100.72		100.62		100.48
28	0.280688791	105.332		100		100		100		21.456		21.428
29	0.304079523		225.76		175.77		125.76		100.41		100.62	
30	0.304079523		100		100		100		100		21.456	
31	0.327470256	250.773		200.74		150.79		100.72		100.75		100.61
32	0.327470256	105.332		100		100		100		21.484		21.456
33	0.350860989		225.76		175.77		125.76		100.41		100.75	
34	0.350860989		100		100		100		100		21.484	
35	0.374251721	250.773		200.74		150.79		100.72		100.88		100.75
36	0.374251721	105.332		100		100		100		21.512		21.484
37	0.397642454		225.76		175.77		125.76		100.41		100.88	
38	0.397642454		100		100		100		100		21.512	
39	0.421033186	250.773		200.74		150.79		100.72		101.01		100.88
40	0.421033186	105.332		100		100		100		21.539		21.512
41	0.444423919		225.76		175.77		125.76		100.41		101.01	
42	0.444423919		100		100		100		100		21.539	
43	0.467814651	250.773		200.74		150.79		100.72		101.14		101
44	0.467814651	105.332		100		100		100		21.567		21.539
45	0.491205384		225.76		175.77		125.76		100.41		101.14	
46	0.491205384		100		100		100		100		21.567	
47	0.514596117	250.773		200.74		150.79		100.72		101.27		101.13
48	0.514596117	105.332		100		100		100		21.595		21.567
49	0.537986849		225.76		175.77		125.76		100.41		101.27	
50	0.537986849		100		100		100		100		21.595	
51	0.561377582	250.773		200.74		150.79		100.72		101.4		101.26

Hydraulic Transient – Piezometric Head Output

	1	2	3	4	5	6	7
1		0	200	400	600	800	1000
2	2.572981	250.7726	200.7398	150.7905	107.8102	128.5901	213.6325
3	Max	250.7726	200.7398	150.7905	107.9757	202.8482	284.5399
4	Min	250.7726	200.7398	150.7905	100.7202	11.77671	1.323302
5	0	250.7726	200.7398	150.7905	100.7202	100.0956	100
6	0.046781	250.7726	200.7398	150.7905	100.7202	100.0956	284.5016
7	0.093563	250.7726	200.7398	150.7905	100.7202	100.1607	284.5399
8	0.140344	250.7726	200.7398	150.7905	100.7202	100.2258	100.1549
9	0.187126	250.7726	200.7398	150.7905	100.7202	100.3559	100.2223
10	0.233907	250.7726	200.7398	150.7905	100.7202	100.4861	100.3547
11	0.280689	250.7726	200.7398	150.7905	100.7202	100.6162	100.4848
12	0.32747	250.7726	200.7398	150.7905	100.7202	100.7463	100.6149
13	0.374252	250.7726	200.7398	150.7905	100.7202	100.8763	100.745
14	0.421033	250.7726	200.7398	150.7905	100.7202	101.0063	100.875
15	0.467815	250.7726	200.7398	150.7905	100.7202	101.1362	101.005
16	0.514596	250.7726	200.7398	150.7905	100.7202	101.2661	101.1349
17	0.561378	250.7726	200.7398	150.7905	100.7202	101.3959	101.2648
18	0.608159	250.7726	200.7398	150.7905	100.7202	101.5257	101.3946
19	0.654941	250.7726	200.7398	150.7905	100.7202	101.6555	101.5244
20	0.701722	250.7726	200.7398	150.7905	100.7202	101.7852	101.6542
21	0.748503	250.7726	200.7398	150.7905	100.7202	101.9148	101.7839
22	0.795285	250.7726	200.7398	150.7905	100.7202	102.0444	101.9135
23	0.842066	250.7726	200.7398	150.7905	100.7202	102.174	102.0431
24	0.888848	250.7726	200.7398	150.7905	100.7202	102.3035	102.1727
25	0.935629	250.7726	200.7398	150.7905	100.7202	102.433	102.3022
26	0.982411	250.7726	200.7398	150.7905	100.7202	102.5624	102.4317
27	1.029192	250.7726	200.7398	150.7905	100.7202	102.6918	102.5611
28	1.075974	250.7726	200.7398	150.7905	100.7202	102.8211	102.6905
29	1.122755	250.7726	200.7398	150.7905	100.7202	102.9504	102.8198
30	1.169537	250.7726	200.7398	150.7905	100.7202	103.0796	102.9491
31	1.216318	250.7726	200.7398	150.7905	100.7202	103.2088	103.0783
32	1.2631	250.7726	200.7398	150.7905	100.7202	103.338	103.2075
33	1.309881	250.7726	200.7398	150.7905	100.7202	103.4671	103.3367
34	1.356662	250.7726	200.7398	150.7905	100.7202	103.5962	103.4658
35	1.403444	250.7726	200.7398	150.7905	100.7202	103.7252	103.5948
36	1.450225	250.7726	200.7398	150.7905	100.7202	103.8541	103.7238
37	1.497007	250.7726	200.7398	150.7905	100.7202	103.9831	103.8528
38	1.543788	250.7726	200.7398	150.7905	100.7202	104.1119	103.9817
39	1.59057	250.7726	200.7398	150.7905	100.7202	104.2408	104.1106
40	1.637351	250.7726	200.7398	150.7905	100.7202	104.3696	104.2394
41	1.684133	250.7726	200.7398	150.7905	100.7202	104.4983	104.3682
42	1.730914	250.7726	200.7398	150.7905	100.7202	104.627	104.4969
43	1.777696	250.7726	200.7398	150.7905	100.7202	104.7557	104.6256

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