NUMERICAL SIMULATIONS OF UNSTEADY FLOW IN AN OIL PIPELINE UNDER VARIOUS HYDRAULIC CONDITIONS

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ABSTRACT

NUMERICAL SIMULATIONS OF UNSTEADY FLOW IN AN OIL PIPELINE UNDER VARIOUS HYDRAULIC CONDITIONS

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In the present study, transient flow analyses of a long oil pipeline are performed. Transient flow conditions are initiated by typical valve operations and pump trips that may be expected during operation of such pipelines. In order to simulate transient events an existing computer program called "Stoner Pipeline Simulator" has been used for a large number of hydraulic transient conditions. The program is based on the characteristics method solution of the governing water hammer equations. Locations that may be subject to surge pressures of high magnitudes, even exceeding maximum allowable pressure limit have been determined by the program. In the present study, a number of measures to control and preferably to avoid these undesirable surge pressures are also covered. Guidelines for safe operation of the pipeline are developed and suggested for the use of technical personnel.

Keywords: Oil Pipeline, Numerical Simulation, Unsteady Flow

ÖZ

ÇEŞİTLİ HİDROLİK KOŞULLAR ALTINDA BİR PETROL BORU HATTINDAKİ ZAMANA BAĞLI AKIMIN NÜMERİK BENZEŞİMİ

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Bu çalışmada uzun bir petrol boru hattının zamana bağlı akım analizleri gerçekleştirilmiştir. Zamana bağlı akım durumları bu tip boru hatlarının işletilmeleri sırasında beklenen tipik vana operasyonları ve ani pompa durmalarından kaynaklanmaktadır.Bu tür akımların benzeşimi için, zamanla değişen ve çok sayıda hidrolik akım koşullarında kullanılan "Stoner Pipeline Simulator" isimli mevcut bir program kullanılmıştır. Program su koçu denklemlerinin karakteristikler metodu ile çözümünü içermektedir. Bu program tarafından yüksek dalga basınçlarının, hatta izin verilebilir en yüksek basınç sınırlarını aşan dalga basınçlarının yerleri tespit edilmiştir. Bu çalışmada istenmeyen büyüklükteki dalga basınçlarından kaçınmak için gerekli önlemler de anlatılmıştır. Boru hattının güvenli işletme koşulları geliştirilmiş ve teknik personelin kullanımı için tavsiye edilmiştir.

Anahtar Kelimeler: Petrol Boru Hattı, Sayısal Benzeşim, Zamana bağlı akım

To

My Family

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LIST OF SYMBOLS AND ABBREVIATIONS

A	cross-sectional area of pipe
a	Wave speed
ACG	Azeri, Chirag and Guneshli
Az	Azerbaijan
B	a parameter used in equations
barg	bar gauge
bpd	barrels per day
BTC	Baku - Tbilisi – Ceyhan
c	wave speed in fluid
C^+,C^-	Name for characteristics equations
C_M,C_P	known constants in characteristics equations
D	diameter of the pipe
D/t	Station Safety Sequence
DRA	Diameter / wall thickness ratio
E	modulus of elasticity
e	pipe thickness
Eqn.	equation
ESD	Emergency Shutdown System
f	Darcy-Weisbach friction factor
F	Force,N
F_r	Froude Number.
ft	feet.
g	gravitational acceleration, m/s^2.
h	dimensionless pressure head
id	Internal diameter of pipe
HPTxx	Highpoint in the longitudinal profile of the Turkish section
H_P	piezometric head at unknown computational point in -xt plane of characteristics grid
H_R	elevation of the reservoir surface
IPTx	Intermediate Pigging Station
K	bulk modulus of elasticity
KP	pipe kilometre
L	pipe length
L_1, L_2	identification of continuity and momentum eqn in characteristics method

m/s	metre per second
MAOP	Maximum Allowable Operating Pressure
MATP	Maximum Allowable Transient Pressure
MOP	Maximum Operating Pressure
MTA	Million Ton Annual
MTBF	Mean Time Between Failure
MTBM	Mean Time Between Maintenance
n	the Manning's resistance coefficient
NPSH	Net Positive Suction Head
OD	outside diameter of pipe
P	pressure
PE	Polyethylene
PRES	Initial Pressure Along the Pipeline
PTx	Pumping Station in the Turkish Section of the Pipeline
R	a coefficient related to friction loss
r	pipe radius
RTU	Remote Telemetry Unit
SCADA	Supervision Control And Data Acquisition
SPS	Stoner Pipeline Simulator
SSS	Station Safety Sequence
T	temperature
t	time, second or thickness (mm)
TT1	Ceyhan Export Terminal (Station Inlet)
x	Pipe axial direction
V	instantaneous air velocity
ω	Circular frequency
ϵ_s	roughness of pipe
ΔH	increment of head change
ΔV	increment of flow velocity
Δt	time step in iteration scheme
°C	degrees Celsius
μ	dynamic viscosity ,Ns/m^2
ά	dimensionless speed ratio
ν	kinematics viscosity
λ	multiplier in characteristics method
τ	dimensionless parameter for valve opening
τ_w	wall shear stress
ρ	density of fluid kg/m^3
γ	Specific weight of the fluid

CHAPTER 1

INTRODUCTION

Liquid pipelines can not be designed just considering the steady state flow analyses alone. They are also subjected to transient operating conditions. Because of that the designer should need the precise information on the magnitude, timing and economical control methods for the hydraulic transients that may be initiated during liquid pipeline system start-up, valve operations, routine and emergency shutdown, pump trips, etc. All of these excitations change the flow rate in the pipeline.

As a result of changes in fluid flow velocities, water hammer may be generated subjecting system components to excessive dynamic loading. During the design stage of a fluid flow system, it is therefore necessary to investigate these transient operating conditions and consider appropriate solutions suppressing water hammer.
The calculation of transients in a fluid flow system requires a reliable mathematical model. A typical mathematical model consists of two main parts;

- The modelling of the various components of a pipeline such as pumps, valves etc. which constitute the boundary conditions
- The description of the propagation of the pressure waves in the pipeline, based on the solution of governing unsteady flow equations using the initial and boundary conditions of the pipeline

The propagation of the pressure waves is described by means of two coupled partial differential equations; the equation of motion and the continuity equation. The pipeline components make up the boundary conditions for the solution of these differential equations, along with the initial steady-state conditions.

The computer program used in the current study is based on the momentum and continuity equations as simultaneously solved partial differential equations. By using the method of characteristics, these two equations are transformed into four ordinary differential equations and are then numerically integrated and a transient analysis for all critical load cases and events was carried out to ensure the integrity of the Baku-Tbilisi-Ceyhan (BTC), Crude Oil Pipeline system. The most important cases and the detailed calculations and results are part of this study.

A simulation model of the BTC Crude Oil Pipeline transportation system has been developed to assess storage requirements at Ceyhan Terminal, marine export facilities at Ceyhan and overall system availability. The model has a generic structure to enable a number of interested parties to use it in conjunction with Run-Only software. The transient simulations demonstrate that operation within the allowable operating pressures is possible. The gradients prepared for normal operation will not exceed the maximum allowable operating pressures (MAOP) of the pipeline at any time. In some load cases the MAOP of the pipeline is exceeded. However, the 10% overpressure line is never exceeded at any point.

The required volume for the relief tanks in different stations was also determined during the transient analysis.

The structure of the program allows a user to select various configurations of key equipment (storage tanks, pump stations, pumps, marine export facilities, etc.) to determine total or partial system availability.

1.2 Literature Survey

Menebrea‘s notes (1858) is the earliest published analysis of water hammer. He contributed to the theory of elasticity so that his approach to the water hammer problem is not from a consideration of the fluid flow, but from the deformation of the elastic elements involved and also, rather than using momentum or continuity, he proposed an energy analysis. Menebreas's method occupies an important position in the history of water hammer. Unfortunately he did not identify the wave celerity.

Joukowsky (1898) has been widely accepted as the founder of modern water hammer theory. The velocity of a water hammer wave inside a rigid pipe is $a = \sqrt{\frac{K}{\rho}}$ where K is the bulk modulus of fluid and ρ fluid density .It is well known that this velocity is reduced if the pipe is elastic and that the reduction depends on the size of the pipe, its elastic properties and the external constraints. However, there is a difference between Halliwell's (1963) and Joukowsky's approach when considering the amount of this reduction.

To sum up, Joukowsky stated that the effect of the elasticity of the pipeline on the velocity of the water hammer wave is considerable, whereas the effect of different external constraints on the pipeline is not so great. The velocity may be reduced by a factor of ten or more because of the elasticity of the pipeline, but the variation in this reduced velocity due to various external constraints, in general, less than 10 %.

In transient flow through closed conduits, the common concern of the hydraulics engineer is to control the effect of pressure waves in order to protect the relevant system components. The most significant pressure wave is usually water hammer wave produced by the closure of a valve or gate. In this connection, a method known as optimum valve closure, Ruus (1957) allows a valve-closure schedule to be determined so that the maximum pressure does not exceed a specific limit. The concept was later developed for frictionless flow by Cabelka & Franc (1959) and for frictional flow by Streeter (1963). Streeter called his method valve stroking by which the stresses are reduced in pipes and eliminated vibration and reversal of flow caused by water hammer. The definition includes the provision of non residual transients after valve closure; with heads during closure no lower than the initial steady-state value. Later, the method was extended and computerized for complex pipe systems. (Streeter 1967) The method has since been applied by other investigators to different flow conditions. (Driels 1974, Ikeo & Kobori 1975)

CHAPTER 2

NUMERICAL SOLUTION OF TRANSIENT FLOW IN PIPELINES

A numerical solution of the equations that govern unsteady-fluid flow in pipelines is developed in this chapter. A general solution to the partial differential equations is not available; however, the partial differential equations may be transformed by the method of characteristics into particular total differential equations. Next, they may be integrated to obtain finite difference equations which are conveniently handled numerically.

We speak of an unsteady or transient condition if the flow conditions in a pipeline section change during an investigated time period. The discharge, the flow velocity and the pressures change within a considered time period. This change sometimes takes place within a few seconds.

During design stage, computation of the maximum pressures developing due to transient conditions occurring in case of valve closing, pump shut-down etc., is of importance, because in all such cases the pressures produced exceed the pressure under steady state conditions and therefore determine the choice of pipe wall thickness, set pressures for relief-valve systems and other important parameters.

2.1 Derivation of The Governing Equations of Unsteady Pipeflow

The governing partial differential equations are derived in this section under commonly used assumptions which are;

1) Control Volume is nontranslating (fixed).
2) Fluid is single-phase liquid and is "slightly" compressible.

3) Conduit is elastic and constant cross-section.

4) Flow and wave motions are one dimensional, i.e. planar.

2.1.1 Conservation of Mass (Continuity Principle)

The starting integral equation for the conservation of mass, based on the above assumptions can be written as;

$$\frac{\partial}{\partial t}\int_{CV}\rho\, d\forall + \sum_{CS}\rho A(\vec{V}\cdot\hat{n}) = 0 \qquad (2.1)$$

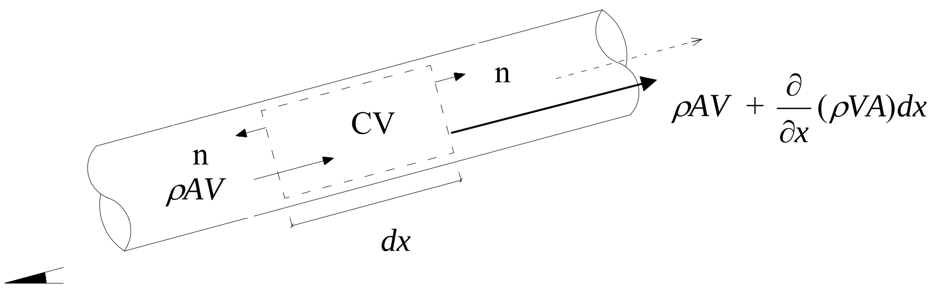

Figure 2.1 Control Volume in a Pipe Element

Considering the control volume in a pipe element in Fig.2.1, Equation 2.1 can be put in the following form

$$\frac{\partial}{\partial t}\int_{CV}\rho\, d\forall = \frac{\partial}{\partial t}\left(\rho\int_{CV} d\forall\right) = \frac{\partial}{\partial t}(\rho A dx) = \frac{\partial}{\partial t}(\rho A)dx \qquad (2.2)$$

$$\sum_{CS}\rho A(\vec{V}\cdot\hat{n}) = \sum_{CS}\rho VA = \left[\rho VA + \frac{\partial}{\partial x}(\rho VA)dx\right] - \rho VA = \frac{\partial}{\partial x}(\rho VA)dx \qquad (2.3)$$

where ρ is the fluid density, V, the average pipe velocity , A, the pipe cross-sectional area, dx, the differential element length.

$$\frac{\partial}{\partial t}(\rho A)dx + \frac{\partial}{\partial x}(\rho AV)dx = 0$$ If it is divided by dx,

$$\frac{\partial(\rho A)}{\partial t} + \frac{\partial(\rho AV)}{\partial x} = 0$$ then if differentiated by parts and rearranged

$$\rho\frac{\partial A}{\partial t} + A\frac{\partial \rho}{\partial t} + \rho A\frac{\partial V}{\partial x} + AV\frac{\partial \rho}{\partial x} + \rho V\frac{\partial A}{\partial x} = 0$$

Then recall the following relations,

$$\frac{d\rho}{\rho} = \frac{dP}{K} \quad \& \quad \frac{dA}{A} = \frac{D.dP}{E.e} \quad \text{or} \quad \frac{dA}{A} = \frac{D.c_1}{E.e}dP \quad (c_1 \approx 1)$$

where dP is the incremental pressure, D, the pipe diameter ,E ,the elasticity modulus of pipe material, K, the bulk modulus of fluid, e, the pipe thickness, c_1, a constant based on external constraints.

Substitute those and divide by ρA to get

$$\frac{1}{K}\left(\frac{\partial P}{\partial t} + V\frac{\partial P}{\partial x}\right) + \frac{D}{E.e}\left(\frac{\partial P}{\partial t} + V\frac{\partial P}{\partial x}\right) + \frac{\partial V}{\partial x} = 0$$

$$\left(\frac{1}{K} + \frac{D}{E.e}\right)\left(\frac{\partial P}{\partial t} + V\frac{\partial P}{\partial x}\right) + \frac{\partial V}{\partial x} = 0$$

$$\left(\frac{\partial P}{\partial t} + V\frac{\partial P}{\partial x}\right) + \frac{1}{\left(\frac{1}{K} + \frac{D}{E.e}\right)}\frac{\partial V}{\partial x} = 0$$ The coefficient of $\frac{\partial V}{\partial x}$ can be rearranged as

$$\frac{1}{\left(\frac{1}{K} + \frac{D}{E.e}\right)} \cdot \frac{\left(\frac{K}{\rho}\right)\rho}{K} = \rho\frac{\left(\frac{K}{\rho}\right)}{\left(1 + \frac{K.D}{E.e}\right)} = \rho.a^2$$ where a is the pressure wave speed in

the pipe and is equal to $\sqrt{\frac{\left(\frac{K}{\rho}\right)}{\left(1 + \frac{K.D}{E.e}\right).c_1}}$ (2.4)

Then, $(\frac{\partial P}{\partial t}+V\frac{\partial P}{\partial x})+\rho a^2\frac{\partial V}{\partial x}=0$ forms, and we can divide by ρ to get

$$\frac{1}{\rho}(\frac{\partial P}{\partial t}+V\frac{\partial P}{\partial x})+a^2\frac{\partial V}{\partial x}=0 \quad \text{the continuity equation} \qquad (2.5)$$

2.1.2 Conservation of Momentum

Conservation of Momentum can be stated as

$$\sum F_x=\frac{\partial}{\partial t}\int_{CV}\rho\vec{V}\,d\forall+\sum_{CS}\rho V_x\,(\vec{V}\cdot\hat{n})A \qquad (2.6)$$

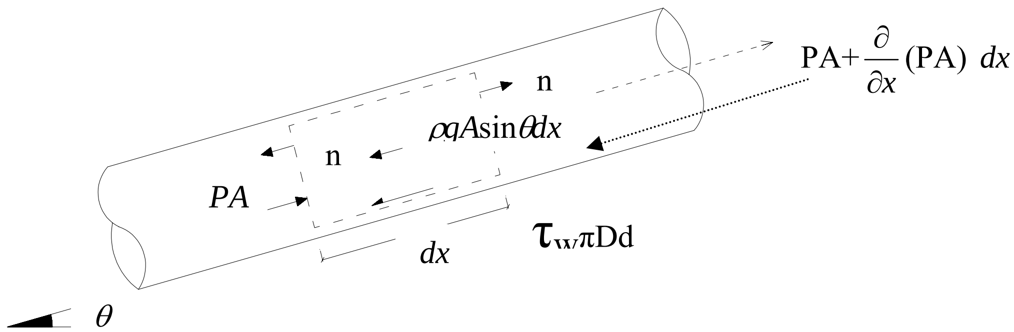

Figure 2.2 Control Volume for Conservation of Momentum

Where τ_w is the wall shear stress, P, the pressure acting across the control surface. Considering the control volume in Fig.2.2, Eqn 2.6 can be expanded in the following form;

$$\sum F_x=PA-\left[PA+\frac{\partial}{\partial x}(PA)\,dx\right]-\tau_w\,\pi\,D\,dx-\rho\,g\,A\sin\theta\,dx \qquad (2.7)$$

By neglecting second order effect of changes in pipe area due to pressure changes (i.e. $P\dfrac{\partial A}{\partial x}dx$)

$$\sum F_x \cong -(A\frac{\partial P}{\partial x} + \tau_w \pi D + \rho g A\sin\theta)\,dx \tag{2.8}$$

$$\frac{\partial}{\partial t}\int_{CV}\rho\vec{V}\,d\forall = \frac{\partial}{\partial t}(\rho V\int_{CV}d\forall) = \frac{\partial}{\partial t}(\rho VA)\,dx$$

$$\sum_{CS}\rho V_x(\vec{V}\cdot\hat{n})A = \sum_{CS}\rho V^2 A = \left[\rho V^2 A + \frac{\partial}{\partial x}(\rho V^2 A)\,dx - \rho V^2 A\right] = \frac{\partial}{\partial x}(\rho V^2 A)\,dx$$

$$-(A\frac{\partial P}{\partial x} + \tau_w \pi D + \rho g A\sin\theta)\,dx = \frac{\partial}{\partial t}(\rho VA)\,dx + \frac{\partial}{\partial x}(\rho V^2 A)\,dx$$

Right side can be expanded

$$\frac{\partial}{\partial t}(\rho VA) + \frac{\partial}{\partial x}(\rho V^2 A) = V\underbrace{\left[\frac{\partial}{\partial t}(\rho A) + \frac{\partial}{\partial x}(\rho VA)\right]}_{\text{This is the continuity equation which is equal to zero}} + \rho A(\frac{\partial V}{\partial t} + V\frac{\partial V}{\partial x}) \tag{2.9}$$

By dividing by ρA & using A= $\pi D^2/4$ we obtain

$$-(\frac{1}{\rho}\frac{\partial P}{\partial x} + \frac{4\tau_w}{\rho D} + g\sin\theta) = \frac{\partial V}{\partial t} + V\frac{\partial V}{\partial x}$$

$$\frac{1}{\rho}\frac{\partial P}{\partial x} + \frac{\partial V}{\partial t} + V\frac{\partial V}{\partial x} + (\frac{4\tau_w}{\rho D} + g\sin\theta) = 0 \qquad \text{Momentum Equation} \tag{2.10}$$

2.2 The Method of Characterictics

The continuity and momentum equations derived in the preceding section form a pair of quasi –linear hyperbolic partial differential equations in terms of two dependent variables, velocity and pressure, and two independent variables, distance, x along the pipeline and time, t. The equations are transformed into four ordinary differential equations by the method of characteristics.

The method of characteristic has many advantages:

- Stability criteria are firmly established
- Boundary conditions are easily programmed
- Minor terms may be retained if desired
- Very complex systems may be handled
- It has the best accuracy of any of the finite difference methods
- Programs are easy to debug because steady state satisfies all conditions, and an error in programming shows up as a change from steady state
- It is a detailed method which allows complete tabular results to be printed out.

By using the continuity and momentum equations, independent variables are x and t; dependent variables are P(x,t) & V(x,t) for which we want to solve these two hyperbolic partial differential equations

$$\frac{1}{\rho}\left(\frac{\partial P}{\partial t}+V\frac{\partial P}{\partial x}\right)+a^2\frac{\partial V}{\partial x}=0 \quad \text{Continuity Equation} \qquad (2.11)$$

$$\frac{1}{\rho}\frac{\partial P}{\partial x}+\frac{\partial V}{\partial t}+V\frac{\partial V}{\partial x}+\left(\frac{4\tau_w}{\rho D}+g\sin\theta\right)=0 \quad \text{Momentum Equation} \qquad (2.12)$$

Let us define $F=\left(\frac{4\tau_w}{\rho D}+g\sin\theta\right)=F(V)$ then we have;

$$L_1=\frac{\partial P}{\partial t}+V\frac{\partial P}{\partial x}+\rho a^2\frac{\partial V}{\partial x}=0 \qquad (2.13)$$

$$L_2=\frac{\partial V}{\partial t}+V\frac{\partial V}{\partial x}+\frac{1}{\rho}\frac{\partial P}{\partial x}+F=0 \qquad L_1+\lambda L_2=0 \qquad (2.14)$$

where λ is a multiplier.

$$\frac{\partial P}{\partial t} + V\frac{\partial P}{\partial x} + \rho a^2 \frac{\partial V}{\partial x} + \lambda(\frac{\partial V}{\partial t} + V\frac{\partial V}{\partial x} + \frac{1}{\rho}\frac{\partial P}{\partial x} + F) = 0 \tag{2.15}$$

$$\left[\frac{\partial P}{\partial t} + (V + \frac{\lambda}{\rho})\frac{\partial P}{\partial x}\right] + \lambda\left[\frac{\partial V}{\partial t} + (V + \frac{\rho a^2}{\lambda})\frac{\partial V}{\partial x}\right] + \lambda F = 0 \tag{2.16}$$

From Calculus we know that for $\varphi(x,t)$, $\frac{d\varphi}{dt} = \frac{\partial \varphi}{\partial t} + \frac{\partial \varphi}{\partial x}\frac{dx}{dt}$

Therefore, $\frac{\partial P}{\partial t} + (V + \frac{\lambda}{\rho})\frac{\partial P}{\partial x} = \frac{dP}{dt}$ if $V + \frac{\lambda}{\rho} = \frac{dx}{dt}$

Similarly, $\frac{\partial V}{\partial t} + (V + \frac{\rho a^2}{\lambda})\frac{\partial V}{\partial x} = \frac{dV}{dt}$ if $V + \frac{\rho a^2}{\lambda} = \frac{dx}{dt}$

So $L_1 + \lambda L_2 = 0$ becomes $\frac{dP}{dt} + \lambda\frac{dV}{dt} + \lambda F = 0$ subject to constraint

$$\frac{dx}{dt} = (V + \frac{\lambda}{\rho}) = (V + \frac{\rho a^2}{\lambda}) \tag{2.17}$$

Now let us find λ where $V + \frac{\lambda}{\rho} = V + \frac{\rho . a^2}{\lambda}$

$\frac{\lambda}{\rho} = \frac{\rho a^2}{\lambda} \Rightarrow \lambda^2 = \rho^2 a^2 \Rightarrow \lambda = \pm \rho a \qquad \frac{dx}{dt} = V \pm a$

$$\left\{ \frac{1}{\rho}\frac{dP}{dt} + a\frac{dV}{dt} + aF = 0 \qquad \frac{dx}{dt} = V + a \right\} \rightarrow C^+ \tag{2.18}$$

$$\left\{ \frac{1}{\rho}\frac{dP}{dt} - a\frac{dV}{dt} - aF = 0 \qquad \frac{dx}{dt} = V - a \right\} \rightarrow C^- \tag{2.19}$$

since $\frac{dx}{dt} = V \pm a = a(\frac{V}{a} \pm 1)$ and also $1 >> \frac{V}{a}$ then we can write $\frac{dx}{dt} = \pm a$

$$\left\{ \frac{1}{\rho}\frac{dP}{dt} + a\frac{dV}{dt} + aF = 0 \qquad \frac{dx}{dt} = a \qquad \rightarrow C^{+} \right\} \quad (2.20)$$

$$\left\{ \frac{1}{\rho}\frac{dP}{dt} - a\frac{dV}{dt} - aF = 0 \qquad \frac{dx}{dt} = -a \qquad \rightarrow C^{-} \right\} \quad (2.21)$$

Compatibility Equation   Characteristic Equations

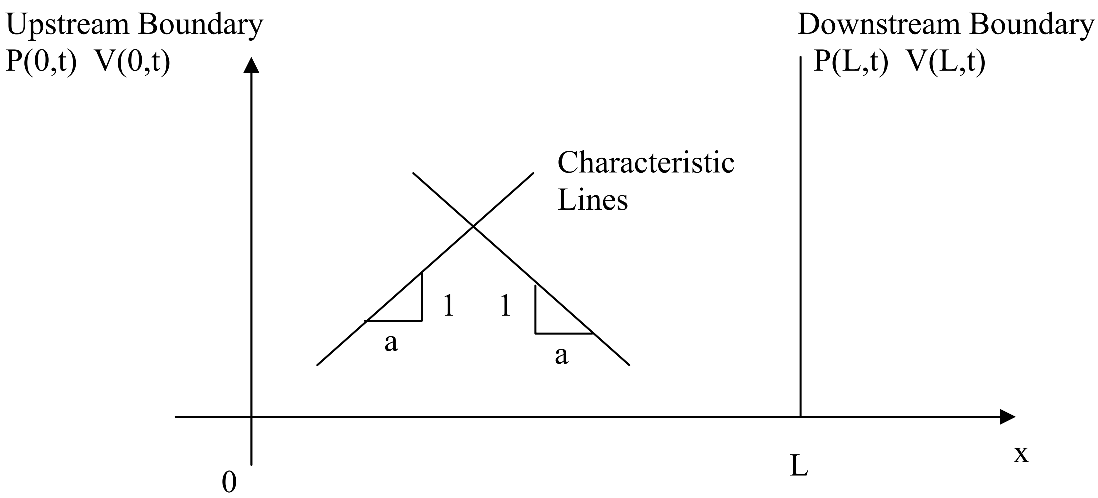

Figure 2.3 A Simple Sketch Showing the Characteristic Lines

The compatibility equations are valid on the characteristic lines.

2.2.1 Finite Difference Equations

So the following equations are derived;

$$\frac{1}{\rho a}\frac{dP}{dt} \pm \frac{dV}{dt} \pm F = 0 \quad (2.22)$$

$$\frac{dx}{dt} \cong \pm a \quad (2.23)$$

these equations should be integrated along respective characteristic direction in the solution domain shown in Fig2.4

$$C^{+} = \frac{1}{\rho a} dP + dV + F\, dt = 0, \qquad dx = a\, dt \tag{2.24}$$

$$C^{-} = \frac{1}{\rho a} dP - dV - F\, dt = 0, \qquad dx = -a\, dt \tag{2.25}$$

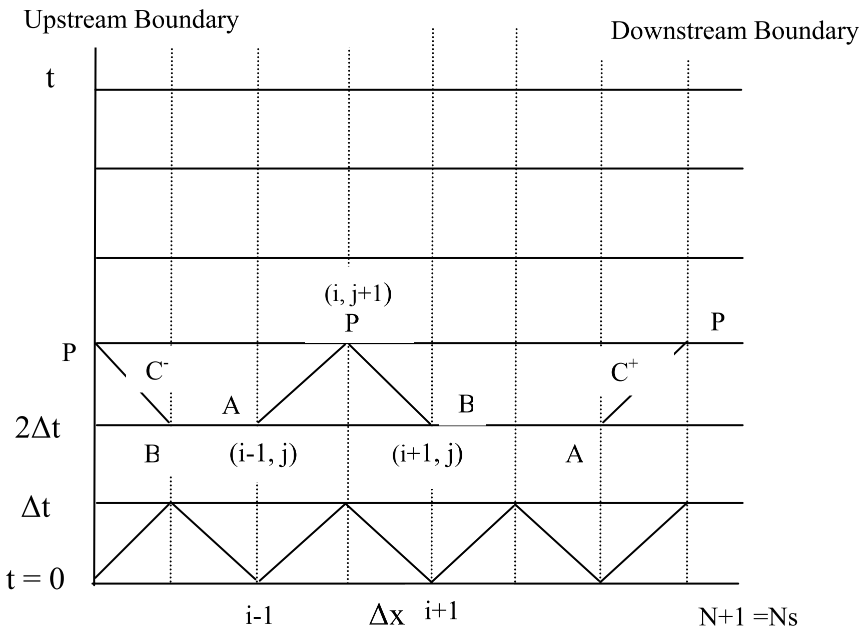

Figure 2.4 Solution Domain

Point P is the location where the unknown pressure P and velocity V are to be computed. P and V are known at locations A and B either from the initial conditions or computed from the previous time step.

$$C^{+} : \int_{A}^{P} \frac{1}{\rho a} dP + \int_{A}^{P} dV + \int_{A}^{P} F dt = 0, \qquad \int_{A}^{P} dx = \int_{A}^{P} a\, dt \tag{2.26}$$

$$C^{-}: \int_B^P \frac{1}{\rho a} dP + \int_B^P dV + \int_B^P F dt = 0, \qquad \int_B^P dx = \int_B^P a\, dt \tag{2.27}$$

$$C^{+}: \frac{1}{\rho a}(P_P - P_A) + (V_P - V_A) + \int_A^P F\, dt = 0, \qquad \Delta x = a\,\Delta t \tag{2.28}$$

$$C^{-}: -\frac{1}{\rho a}(P_P - P_B) + (V_P - V_B) + \int_B^P F\, dt = 0, \qquad \Delta x = -a\,\Delta t \tag{2.29}$$

If "quasi-steady" function is assumed;

$$\frac{4\tau_w}{\rho D} = f\frac{V|V|}{2D} \qquad \int_A^B F\, dt = \int_A^B (g\sin\theta + f\frac{V|V|}{2D})dt = g\sin\theta\,\Delta t + \frac{f}{2D}\int_A^B V|V|dt$$

Using Euler approximation (1st order): $\int_A^B V|V|\,dt \cong V_A|V_A|\Delta t$

$$\int_{t_A}^{t_P} V|V|\,dt \cong V^2 t\Big|_{t_A}^{t_P} - \int_{t_A}^{t_P} t\,dV^2 = V^2 t\Big|_{t_A}^{t_P} - 2\int_{t_A}^{t_P} tV\,dV \approx V_P^{\,2} t_P - V_A^{\,2} t_A - 2\left[\frac{V_P t_P + V_A t_A}{2}(V_P - V_A)\right]$$

$$C^{+}: \int_{t_A}^{t_P} F\, dt \approx g\sin\theta\,\Delta t + \frac{f}{2D} V_A|V_A|\Delta t = G_A$$

$$C^{-}: \int_{t_B}^{t_P} F\, dt \approx g\sin\theta\,\Delta t + \frac{f}{2D} V_B|V_B|\Delta t = G_B$$

$$C^{+} = (P_P - P_A) + \rho a(V_P - V_A) + \rho a G_A = 0$$

$$C^{-} = -(P_P - P_B) + \rho a(V_P - V_B) + \rho a G_B = 0$$

$$V_P = \frac{1}{2}\left[(V_A + V_B) + \frac{1}{\rho a}(P_A - P_B) - (G_A - G_B)\right] \tag{2.30}$$

$$P_P = \frac{1}{2}\left[(P_A + P_B) + \frac{(V_A - V_B)}{\rho a} - \rho a(G_A + G_B)\right] \tag{2.31}$$

The same equations were derived in terms of dependent variables V, velocity and H, piezometric head by Wylie and Streeter (1984) as follows;

$$\left\{ \begin{array}{ll} \frac{g}{a}\frac{dH}{dt} + \frac{dV}{dt} + \frac{fV|V|}{2D} = 0 & \text{Compatibility Eqn.} \quad (2.32) \\ \frac{dx}{dt} = +a & \text{Characteristic Eqn.} \quad (2.33) \end{array} \right\} C^{+}$$

$$\left\{ \begin{array}{ll} \frac{-g}{a}\frac{dH}{dt} + \frac{dV}{dt} + \frac{fV|V|}{2D} = 0 & \text{Compatibility Eqn} \quad (2.34) \\ \frac{dx}{dt} = -a & \text{Characteristic Eqn .} \quad (2.35) \end{array} \right\} C^{-}$$

It is easier to visualize the solution as it develops on the xt plane shown in Figure 2.5

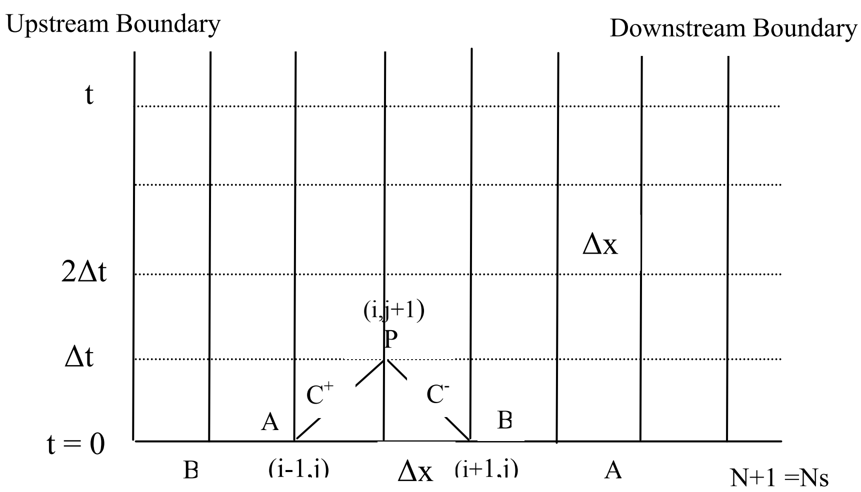

Figure 2.5 xt grid for solving single-pipe problems

If one considers Figure 2.5, a is generally constant for a given pipe, so dx/dt=a & dx/dt=-a plots as a straight line on the x-t plane. These lines are called characteristic lines. Along these lines, the other equations are valid. They are called "compatibility equations".[1] A pipeline is divided into N equal reaches, each Δx in length as shown in the figure above. A time step is computed by using the Courant Condition $\frac{\Delta x}{\Delta t} \le a$ but usually $\frac{\Delta x}{\Delta t} = a$ so that $\Delta t = \frac{\Delta x}{a}$ and Eqn. (2.33) is satisfied by a positively sloped diagonal of the grid, shown by the line AP. If the dependent variables V and H are known at A, then Eqn.(2.32) which is valid along the C^+ line, can be integrated between the limits A and P.

Eqn. (2.35) is satisfied along the line BP , on which Eqn.(2.34) is valid, with conditions known at B. Then we have two equations in two unknowns at point P. A simultaneous solution yields conditions at the particular time and position in the xt plane designated by point P. By multiplying Eqn. (2.32) by $\frac{a\,dt}{g} = \frac{dx}{g}$ and by introducing the pipeline area to write the equations in terms of discharge Q in place of velocity for the C^+ equation we obtain;

Then $$\int_{H_A}^{H_P} dH + \frac{a}{gA}\int_{Q_A}^{Q_P} dQ + \frac{f}{2gDA^2}\int_{X_A}^{X_P} Q|Q|dx = 0 \tag{2.36}$$

The integration of Eqn. (2.36) yields

$$H_P - H_A + \frac{a}{gA}(Q_P - Q_A) + \frac{f\,\Delta x}{2gDA^2} Q_A|Q_A| = 0$$ similarly for the C^- equation we obtain

$$H_P - H_B - \frac{a}{gA}(Q_P - Q_B) - \frac{f\,\Delta x}{2gDA^2} Q_B|Q_B| = 0 \tag{2.37}$$

[1] Finite Difference Equations

By solving for Hp these equations may be written

$$C^+ : \quad H_P = H_A - B(Q_P - Q_A) - RQ_A|Q_A| \tag{2.38}$$

$$C^- : \quad H_P = H_B + B(Q_P - Q_B) + RQ_B|Q_B| \tag{2.39}$$

In which $B = \dfrac{a}{gA}$, $R = \dfrac{f\,\Delta x}{(2gDA^2)}$

These equations must hold for steady flow, which is a special case of unsteady flow. For steady conditions the flows are equal $Q_A=Q_B=Q_P$ and $RQ_A|Q_A|$ is the steady state friction head loss over the reach Δx.

The solution to a problem in liquid transient usually begins with steady state conditions at time zero, so that H & Q are known initial values at each computing section for t=0, Figure 2.5. The solution consists of finding H & Q for each grid point along t=Δt, then proceeding to t=2Δt, until the desired time duration has been covered. Equation (2.38) and (2.39) may be written in simple form as follows;

$$C^+ : \quad H_{Pi} = C_P - BQ_{Pi} \tag{2.40}$$

$$C^- : \quad H_{Pi} = C_M + BQ_{Pi} \tag{2.41}$$

In which C_P and C_M are always known constants when the equations are applied.

$$C_P = H_{i-1} + BQ_{i-1} - RQ_{i-1}|Q_{i-1}| \tag{2.42}$$

$$C_M = H_{i+1} - BQ_{i+1} + RQ_{i+1}|Q_{i+1}| \tag{2.43}$$

By first eliminating Q_{Pi} in Equations (2.40) & (2.41)

$$H_{Pi} = \frac{(C_P + C_M)}{2} \quad , \qquad (2.44)$$

then Q_{Pi} may be found directly from either Equation (2.39) or (2.40)

2.3 Boundary Conditions

In this section, typical boundary conditions will be introduced as in Wylie and Streeter (1984).At either end of a single pipe only one of the compatibility equation is available in the two variables.

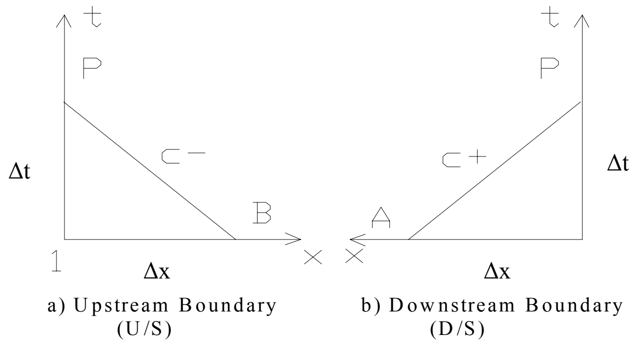

Figure 2.6 Boundary Conditions

For the upstream section Eqn (2.41) holds along the C^- characteristic, and for the downstream Eqn (2.40) is valid along the C^+ characteristic. These are linear equations in Q_P and H_P, each conveys to their respective boundaries the complete behavior and response of the fluid in the pipeline during transient. An auxiliary equation is needed in each case that specifies Q_P, H_P or some relation between them. That is, the auxiliary equation must convey information on the behaviour of the boundary to the pipeline. Each boundary condition is solved independently of the other boundary and independent of the interior point calculations.

2.3.1 Reservoir at Upstream End With Elevation Specified

At a large U/S reservoir the elevation of the hydraulic grade line normally can be assumed constant during a short duration transient. This boundary condition is described as $H_{P1}=H_R$ in which H_R is the elevation of the reservoir surface above the reference datum. If the reservoir level changes in a known manner, say a sine wave the boundary condition is;

$$H_{P1} = H_R + \Delta H \sin wt \tag{2.45}$$

w = circular frequency

ΔH = the amplitude of the wave

At each time step in either of the above cases H_{P1} is known and Q_{P1} is determined by a direct solution of Eqn (2.41)

2.3.2 Discharge as a Specified Function of Time at Upstream End

The flow delivered from a positive displacement pump may be expressed as a function of time,

$$Q_{P1} = Q_0 + \Delta Q |\sin wt| \tag{2.46}$$

with Q_{P1} known at any instant, Eqn (2.41) is applied directly to find H_{P1} at each time step.

2.3.3 Centrifugal Pump at the Upstream End With the Head-Discharge Known

The response of a centrifugal pump operating at constant speed may be included in an analysis by defining the pump characteristic curve.

$$H_{P1} = H_S + Q_{P1} (c_1 + c_2.Q_{P1}) \tag{2.47}$$

In which H_S = shutoff head, c_1 & c_2 are constants to describe the characteristics curve.

Equation (2.47) provides an analytical relationship between the two variables which must be solved simultaneously with equation (2.41). The solution is;

$$Q_{P1} = \frac{1}{2c_2}\left[B - c_1 - \sqrt{(B-c_1)^2 + 4c_2(C_M - H_S)}\right] \tag{2.48}$$

With Q_{P1} known, H_P can be obtained from either Equation (2.41) or (2.47)

2.3.4 Dead End at D/S End of the Pipe

The downstream end of a pipeline that is divided into N reaches is at section Ns = N+1. if the pipeline contains a closed end, then $Q_{P_{NS}} = 0$ *and* $H_{P_{NS}}$ is obtained from either Eqn. (2.40) & (2.41)

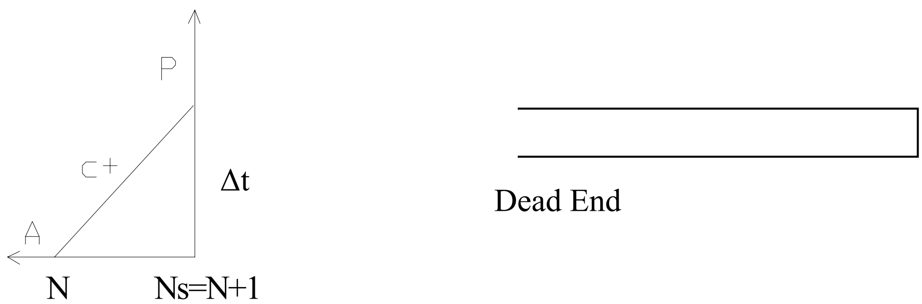

Figure 2.7 Dead End of Pipe

2.3.5 Valve at D/S End of Pipe

If the datum for elevation of hydraulic grade line is taken at the valve, the orifice equation for steady state flow through the valve is

$$Q_0 = (C_D A_V)_0 \sqrt{2gH_0} \quad (2.49)$$

in which Q_0 is the steady state discharge, and H_0, the steady state head loss across the valve and $(C_D A_V)_0$, the area of valve opening times the discharge coefficient

For another opening, in general $Q_P = C_D A_V \sqrt{2g\Delta H}$ (2.50)

In which ΔH is the instantaneous drop in hydraulic grade line across the valve.

After defining the dimensionless valve opening as $\tau = \frac{C_d A_V}{(C_d A_V)_0}$

and dividing Eqn (2.49) by (2.50)

$$Q_P = \frac{Q_0}{\sqrt{H_0}} \tau \sqrt{\Delta H} \quad (2.51)$$

For steady flow $\tau = 1$ and for no flow (valve closed) $\tau = 0$

$\tau > 1$ if the valve is opened from the steady-state position.

After Eqns. (2.40) & (2.51) solved together, we obtain

$$Q_{P_{NS}} = -BC_V + \sqrt{(BC_V)^2 + 2C_V C_P} \quad (2.52)$$

in which $C_V = \frac{(Q_0 \tau)^2}{2H_0}$ (2.53)

2.3.6 Orifice at D/S End of Pipe

The same equations are used for the fixed orifice as for the valve with $\tau = 1$

2.3.7 Surge Tanks

Surge tanks are open tanks connected to the piping system. They take several forms, depending upon their number, arrangement, and the nature of restrictions between the surge tanks and the piping system. In order to accomplish its mission most effectively, the surge tank dimensions and location are based on the following considerations;

- The surge tank should be located as close to the pumping station as possible. The farther the surge tank is away from the plant the less effective it will be.
- The surge tank should be of sufficient height to prevent overflow for all conditions of operation unless an overflow spillway is provided.
- The bottom of the surge tank should be low enough that during its operation the tank will nor drain and admit air into the turbine penstock or pump discharge line.

2.3.8 Pumps

Many of the important transient analysis situations arising from hydraulic design are involved in the start-up or stoppage of pumps and the opening and closing of valves associated with them. By pump failure, the inadvertent stoppage of the pump is meant, without opportunity for prior valve adjustments, as when power is interrupted or safety devices on the pump or motor are actuated due to excessive heating, vibration etc. An operator error in actuating the pump stop button may trigger the same sequence of events. This boundary condition takes the rotary inertia of moving parts into consideration.

CHAPTER 3

THE COMPUTER PROGRAM

3.1 Software

In this study SPS Simulator from Stoner Associates is used for the hydraulic analysis of the pipeline system.

3.2 Stoner Pipeline Simulator

This section is an introduction and overview of the Stoner Pipeline Simulator (SPS). SPS consists of four computer programs:
PREPR: The pre-processor program
TRANS: The transient simulation program
GRAFR: The post-processing program
TPORT: The additional simulation windows program

In addition, the following two utility programs are provided:
TELLTRANS: The background command utility program
DEMAC: The file expansion utility program

SPS is an advanced transient hydraulic modelling program. The user can use it interactively to simulate the dynamic flow of a single fluid, batched fluids or mixed fluids of a single phase through a pipeline network. SPS has the capability to model the operating characteristics of almost any proposed configuration of pipe and equipment; and to predict the outcome of various control strategies to handle operating scenarios such as pipe rupture, equipment failure, or other upset conditions. SPS performs its simulations by calculating flow, pressure, density, temperature and other variables at numerous locations along a pipeline network over time, and studies these values in the form of printed reports and graphs. SPS simulates liquid pipelines including column separation and slack line flow. It does not simulate two-phase flow systems. The simulation can be run either in the background (in a batch mode) or in an interactive mode (the user interacts with the simulation while it is running). The initial state of the simulation can be a zero-flow condition, a user-defined active steady-state condition, or a state saved during a prior simulation.

3.3 How SPS Works

SPS uses detailed data supplied by the user to construct a mathematically sophisticated numerical model of the pipeline system under study. The user has a large collection of building blocks (components) to simulate the user's pipeline network (pumps, pipes, valves, controllers, etc.). These components are modelled after their counterparts in the field. SPS is actually four computer programs: PREPR, TRANS, TPORT, and GRAFR.

3.4 The Preprocessor Program,PREPR

The pre-processor program processes all the mechanical data needed to define the configuration of the user's pipeline system, assembles the components into a working model and generates an "initial state" for the system (to be used as the beginning point for the transient simulation). The PREPR program records all the data to a "restart" file for later input to the transient simulation. PREPR also provides diagnostics for many types of input error and produces an output report in the form of an "echo" print of the input file along with summaries of the initial network parameters and components. The transient simulation program, TRANS uses the initial values produced by PREPR and the simulation control data to perform the transient simulation. The transient simulation is a complex series of calculations that predict the dynamic response of numerous variables all along the network. Running the simulation interactively, the user can change variables and statuses at any time during the simulation and can build and review time and distance plots of any variable that is desired. TRANS produces output in several forms that show the values of important variables for each network component at requested intervals during the transient simulation.

3.5 The Post Processing Program,GRAFR

On request, following the TRANS simulation, both hardcopy reports and graphs of both trends and profiles can be produced. A trend is a report or graph of a certain response at a certain location in the network over time (e.g., the flow at the upstream side of a control valve during a certain span of time). A profile is a reportor graph of a certain response versus distance (e.g., the pressure profile in a pipe at five minutes into the simulation). The format of the reports and graphs is controlled by the set of directives in the INGRAF file.

3.6 Additional Simulation Windows Program,TPORT

TPORT connects to a running TRANS session or to a previously created REVIEW file. If connected to a running TRANS session, TPORT provides additional interactive sessions. All standard TRANS commands may be issued from TPORT. TPORT may be used to review the simulation results of a completed simulation.

3.7 Data Required

The data used by SPS takes several forms; each line of input data must follow certain format rules.

General data (PREPR) include all reference information needed to build the model to simulate the users' network (e.g., standard units, standard reference values, temperature mode setting, equation of state to be used, and friction factor that is to be used for the pipe parameters).

Equipment data (PREPR) include all the information needed to describe the physical components of the users' network (e.g., equipment and control instrument specifications, connections, dimensions, reference settings, performance curves, etc.).

Simulation control data (TRANS) include all the information needed to control the pipeline simulation and to produce interactive time plots or printed reports and distance plots. This category includes details such as time cues for certain events to occur during the simulation (e.g., open/close commands for valves at certain times during the simulation, pump/compressor start/stop commands, etc.), and special commands that control the type and frequency of any output.

Trend/profile data (GRAFR) include specifications for the type of simulation data to be printed as reports or plotted as graphs, plus mechanical specifications such as size, labels and scales of graphs, X-axis, Y-axis, etc.

3.8 Column Seperation

Column separation occurs when pressure down-surges from pump failures or sudden valve closures cause a vapour cavity to form as the pressure drops below the bubble point. Normally only a small fraction of the pipe is occupied by the vapour during column separation. But usually the low pressure region containing the bubbles rapidly accelerates the liquid columns on either side, which produces a sudden collapse of the bubble with a rapid attendant spike in pressure. For column separation calculations to occur, a COLSEP directive must be included in the INTRAN file. The following are general comments on the simulations:

The compressibility of the vapour bubbles is taken into account in calculating the wave speed. In the column separation regime, the wave speed is often quite low because it is related to the bulk modulus of the bubble-containing liquid, which may be only a few hundred psi.

An assumption is made that the fluid is free of entrained gases and that any vapour that forms will go back into solution. If there are entrained gases that dissolve slowly and/or incompletely, SPS calculates a larger surge due to collapse than is experienced in the field. The change in temperature from the collapse of the vapour cavity is not calculated. Therefore, depending upon the tuning parameters described below a different collapse may be calculated than really occurs in the field.

To accurately model column separation and collapse, the user should tune the three COLSEP (INTRAN) input data items, COLAPS, BAND and RATE. The purpose of the dead band is physically justifiable. The simulation assumes that a certain pressure reduction below the bubble point is necessary to initiate nucleation of the bubbles. However, column separation is performed isothermally even if the user has specified TRANSIENT THERMAL mode. As a bubble forms and begins to be filled with vapor and expands, heat is required to form the vapor and support the expansion. This means that the bubble point is lowered (because the temperature is lowered locally). The dead band and rate input parameters provide an attempt to approximate this thermal effect. The collapse of the bubble is similarly associated with thermal effects. As the bubble is compressed, heat is released. This must be conducted into the liquid, raising its temperature and hence its bubble point. Both of these thermal processes have the effect of delaying the phase transfer. The dead band and the collapse rate constants are attempts to approximate the thermal effects of collapse. The default constants are for water at 15.5°C.

Stoner SPS software version 9.3 has been utilized to perform the transient flow and transient hydraulic analysis.

CHAPTER 4

SYSTEM DESCRIPTION

4.1 Pipe Diameter & Pipe Steel

The pipeline diameter is 42-inch in Azerbaijan, 46” (1168.4 mm) in Georgia (up to the first pump station PS-T1 in Turkey), 42” (1066.4 mm) in Turkey except for the final 123.5 kilometres where it reduces to 34” (863.6 mm)as it descends from 1350 m to sea level at Ceyhan. The total length of the pipeline is 1778 km.

The Specified Minimum Yield Strength (SMYS) of the pipe in the Azerbaijan and Georgia section will be 482.6 MPa and for the Turkey section it will be 448.2 MPa. Based on preliminary analysis the wall thickness changes are shown in Table 4.1.

Table 4-1 Wall Thickness Changes

Section	Description
KP 76.81 to KP 100	13.5mm (the 13.5mm wall thickness extended to KP 100)
KP 449.60 to KP 460.00	21.4mm (wall thickness increased from 20.6 to 21.4mm)
KP 702.40 to KP 724.26	wall thickness

There are several pipe wall thickness changes in the Turkish sections as shown in Table 4.1 and some of the changes have been made over a distance of less than 50 m. Installation of the correct wall thickness pipe at the exact location for which a wall thickness change should occur is expected to be a challenge. The pipe has been designed in accordance with ASME B31.4 standard. The maximum allowable operating pressure in the pipe is based on a pipe hoop stress equal to 72 percent of SMYS. The pipe wall thickness requirement is given by the following:

$$t = \frac{pD}{2S} \tag{4-1}$$

Where:

D is the pipe inside diameter in mm

p is the maximum operating pressure in the pipeline, MPa

S is the maximum allowable stress value = 0.72 times SMYS, MPa

t is the pipe wall thickness required, mm

The pipe wall steel requirements were estimated based on the maximum operating pressure in the pipeline. The wall thickness was adjusted to take into account the maximum anticipated surge pressures. Summary of pipe steel requirements are shown in Table 4.2. The total pipe steel requirement is estimated to be 663,210 tons.

Table 4-2 Summary of Pipe Steel Requirements

Outside Pipe Diameter (mm)	Pipe Wall Thickness t (mm)	Pipe SMYS (MPa)	Pipe Length, (km)	Pipe Weight (ton/km)	Total Pipe Weight (ton)
863.6	10.31	448.2	21.052	216.68	4,562
863.6	11.91	448.2	17.561	249.84	4,387
863.6	12.7	448.2	15.406	266.16	4,101
863.6	14.27	448.2	16.279	298.52	4,860
863.6	15.88	448.2	17.600	331.57	5,836
1066.8	10.31	448.2	235.716	268.28	63,238
1066.8	11.91	448.2	173.791	309.45	53,779
1066.8	12.7	448.2	74.600	329.72	24,597

Table 4-2 Summary of Pipe Steel Requirements-(Continued)					
Outside Pipe Diameter (mm)	**Pipe Wall Thickness t (mm)**	**Pipe SMYS (MPa)**	**Pipe Length, (km)**	**Pipe Weight (ton/km)**	**Total Pipe Weight (ton)**
1066.8	13.5	482.6	45.000	350.23	15,760
1066.8	14.27	448.2	94.358	369.93	34,906
1066.8	14.27	482.6	55.591	369.93	20,565
1066.8	15.1	482.6	22.650	391.14	8,859
1066.8	15.88	448.2	135.711	411.04	55,783
1066.8	17.48	448.2	80.629	451.77	36,426
1066.8	19.05	448.2	83.090	491.61	40,848
1066.8	20.62	448.2	46.443	531.33	24,676
1066.8	22.22	448.2	3.811	571.68	2,179
1066.8	23.83	448.2	2.325	612.16	1,423
1168.4	11.91	448.2	8.483	339.25	2,878
1168.4	12.7	448.2	0.850	361.51	307
1168.4	12.7	482.6	26.186	361.51	9,466
1168.4	13.487	482.6	5.162	383.65	1,980
1168.4	14.27	448.2	4.101	405.64	1,664
1168.4	14.27	482.6	10.631	405.64	4,312
1168.4	15.88	448.2	2.353	450.78	1,061
1168.4	15.88	482.6	28.932	450.78	13,042
1168.4	17.5	448.2	1.190	496.07	590
1168.4	17.5	482.6	52.771	496.07	26,178
1168.4	19.05	448.2	3.455	539.28	1,863
1168.4	19.05	482.6	24.443	539.28	13,182
1168.4	20.6	448.2	0.178	582.37	104
1168.4	20.6	482.6	39.881	582.37	23,226
1168.4	21.4	482.6	18.951	604.57	11,457
1168.4	22.22	448.2	1.257	627.28	788

Table 4-2 Summary of Pipe Steel Requirements-(Continued)					
Outside Pipe Diameter (mm)	**Pipe Wall Thickness t (mm)**	**Pipe SMYS (MPa)**	**Pipe Length, (km)**	**Pipe Weight (ton/km)**	**Total Pipe Weight (ton)**
1168.4	23.01	482.6	27.882	649.14	18,099
1168.4	23.825	482.6	17.961	671.65	12,064
		Totals	**1778.279**		**663,213**

4.2 Pump Stations

Both Azerbaijan and Georgia has two pump stations and Turkey has four pump stations along the pipeline. These sections are designated as A1 and A2 for the Azerbaijan section, G1 and G2 for the Georgia section and, T1 through T4 for the Turkey section. For the Stoner model, the pump stations are numbered consecutively from Station 1 to Station 8.

The locations and elevations of the pump stations with respect to mean sea level are summarized in Table 4.3. Note that there is a large static head to overcome at pump stations PS-G1, PS-G2, PS-T1 and PS-T3. There is a large drop in elevation following the high point near KP1541. A pressure reducing station is provided at KP1654.7 to reduce the extent of slack flow. It would also be used to isolate the upstream section of the pipe in order to reduce downstream static head during shutdown.

Table 4-3 Pump Stations Locations

Pump Station	Location, km	Elevation, m
PS-A1	0	-11.3
PS-A2	245.4	56.0
PS-G1	449.6	293.0

Table 4-3 Pump Stations Locations-(Continued)		
Pump Station	**Location, km**	**Elevation, m**
PS-G2	535.7	1368.0
PS-T1	724.4	2149.5
PS-T2	984.1	1718.0
PS-T3	1156.3	2028.0
PS-T4	1457.4	1580.0

Four operating and one standby spare pump will be provided at pump stations PS-A1, PS-G1, PS-G2, PS-T1 and PS-T3 pump stations. These will be centrifugal pumps operating in parallel. Three operating and one standby pumps will be installed at the remaining three pump stations. The pumps at pump stations PS-T2 and PS-T4 will operate in series while the pumps at PS-A2 will operate in parallel. Table 4-4 summarizes the design capacity of the mainline pumps.

Flow control will be used for the mainline pumps at A1. The remaining pump stations will be operated on suction pressure control. The suction pressure will be adjusted to reduce the extent of slack flow. The pump head includes allowance for station losses.

Table 4.4 Design Capacity of Mainline Pumps

Pump Station	Pumps		Flow per Pump, m^3/h	Pump TDH, m	Pump Power, kW	Driver Power, kW
	No.	Operation				
A1	4	Parallel	1675	1072	5750	6380
A2	3	Parallel	2233	1052	7310	8350
G1	4	Parallel	1675	1072	5750	6380
G2	4	Parallel	1675	1072	5750	6380
T1	4	Parallel	1675	1120	4430	5500
T2	3	Series	6700	238	3586	5000
T3	4	Parallel	1675	1140	4524	5500
T4	3	Series	6700	258	3918	5000

Figure 4-1 and Fig 4-2 shows respectively head and efficiency curves of the pump stations PS-T1 and PS-T2

4.2.1 Pressure Reducing Valves

Pressure reducing valves are provided on the suction side of pump stations six (T2) and eight (T4) as well as at pressure reducing stations at km 1654.7 and at the Ceyhan Terminal. The pressure reducing valves are used to apply back pressure to reduce slack flow in the pipeline during normal operations.

4.2.2 Relief System

Surge relief systems have been provided in order to protect the pipe against over pressure conditions at locations summarized in Table 4-5. Tanks are provided to store the crude oil released through these valves.

Table 4.5: Summary of Surge Relief System

Location	Set Point Pressure, kPa	Storage Capacity, m^3
Pump Station 3 (G1)	5,000	2,500
Pump Station 5 (T1)	3,400	3,600
Pump Station 6 (T2)	7,960	8,000
Pump Station 7 (T3)	1,730	6,400
Pump Station 8 (T4)	8,040	11,000
IPT-1 - Pig Station	6,200	6,800
TT1 - Terminal	3,900	11,100

4.2.3 Control System Set Points

The set points used for the control of the pump station are summarized in Table 4.6 These set points were used in the Stoner model for the transient flow as well as transient analysis

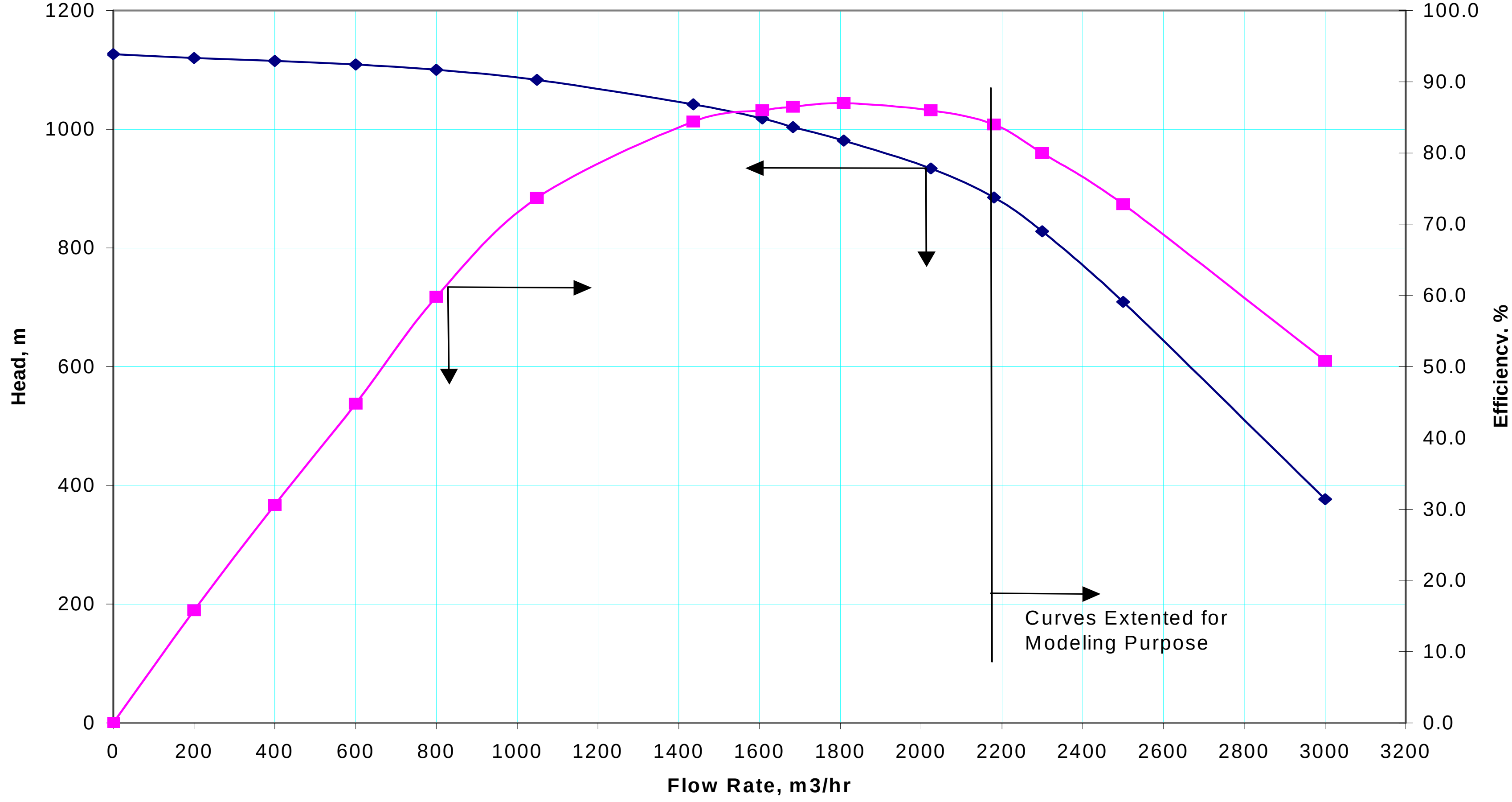

Fig 4.1 Head and Efficieny Curves for PS-T1 Pumps

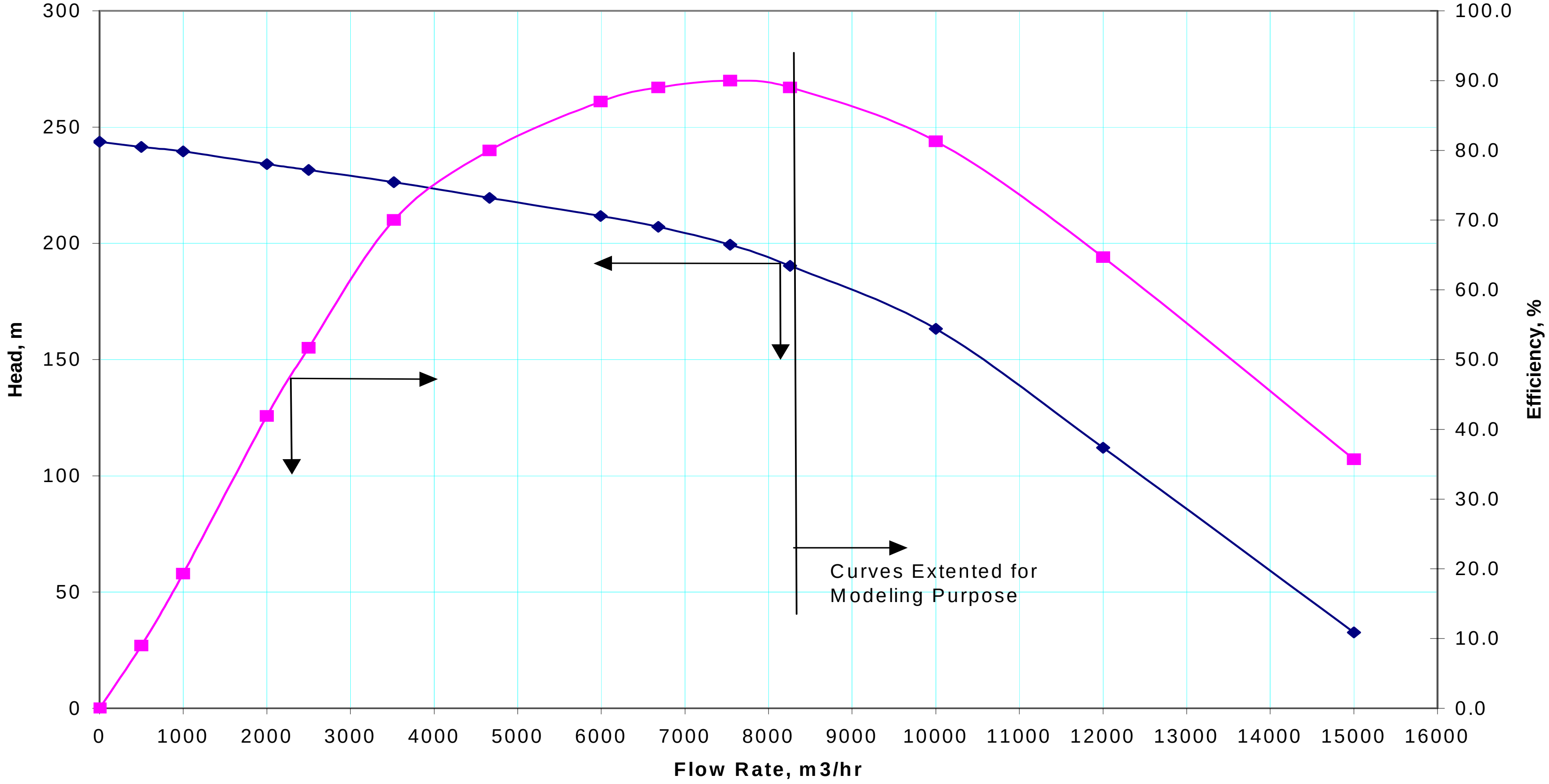

Fig 4.2 Head and Efficiency Curves for PS-T2 Pumps

Table 4-6: Pumping Requirements & Pump Stations Control Set Points

PUMP STATION SET POINTS 03/07 00:00:00

[MENU]

	SUCTION TRIP SET POINT	SUCTION CONTROL SET POINT	STATION SUCTION PRESSURE	PUMP SUCTION PRESSURE	PUMP DISCHARGE PRESSURE	STATION DISCHARGE PRESSURE	DISCHARGE CONTROLLER SET POINT	DISCHARGE TRIP SET POINT		STANDARD FLOW RATE	
A1	575.00	725.00	799.60	673.75	9297.67	9213.58	9500.00	9650.00	KPAG	50.0	MTA
A2	700.00	800.00	800.00	673.71	9342.45	9257.79	9500.00	9650.00	KPAG	50.0	MTA
G1	575.00	725.00	725.00	599.24	11588.29	11504.37	11700.00	11850.00	KPAG	50.0	MTA
G2	575.00	725.00	725.00	599.32	11310.91	11227.03	11500.00	11650.00	KPAG	50.0	MTA
T1	450.00	700.00	700.00	574.62	8718.39	8612.56	8950.00	9100.00	KPAG	50.0	MTA
T2	450.00	3500.00	3500.00	3376.11 5334.09 7296.03	5334.49 7296.43 9262.24	9014.24	9300.00	9450.00	KPAG	50.0	MTA
T3	450.00	700.00	700.00	574.89	9050.24	8944.65	9300.00	9450.00	KPAG	50.0	MTA
T4	450.00	2000.00	2000.00	1876.14 4111.72 6352.45	4112.12 6352.85 8598.58	8350.76	8650.00	8800.00	KPAG	50.0	MTA

4.3 Hydraulic Design Basis

The BTC Pipeline Facilities comprises a regional crude oil export transportation system that spans from the Baku (Sangachal) Terminal located in Azerbaijan, through Tbilisi in Georgia to the existing Ceyhan Terminal Complex located in Turkey. The transported crude oil shall be processed and exported to potential consumers. The pipeline is 42-inch diameter in Azerbaijan, 46" diameter in Georgia (up to the first pump station PS#T1 in Turkey), 42" diameter in Turkey except for the final 120.36 kilometres where it reduces to 34" as it descends from 1350 m to sea level at Ceyhan. The total length of the pipeline is 1778 km. There are eight pump stations and two pressure reducing stations.

4.3.1 Crude Oil Properties

The BTC System will transport predominantly ACG (Azeri, Chirag and Guneshli) crude, but will also transport other regional crude. ACG crude oil specification is to be used as the Base Case that is 852 kg/m^3, -6°C pour point. The transient analysis is based on the properties of the ACG crude oil

The crude oil properties at various temperatures were estimated based on American Petroleum Institute (API) gravity and viscosity data provided. The crude oil viscosity varies with shear rate. At the initial flow rate of 670m^3/h, the shear rate becomes quite small and the oil viscosity becomes significantly higher compared to the viscosity at design flow rate. The variation in effective viscosity with temperature for selected flow rates is shown in Figure 4-3. The method used for estimating effective viscosity at various flow rates is summarized below;

The viscosity, μ, of the fluid (at a pressure P and temperature T), is given by

$$\mu = \mu_o \, e^{(VPMI \cdot \Delta P + VTMI \cdot \Delta T)} \qquad (4\text{-}2)$$

where:

μ_o, is the base viscosity at Po and To

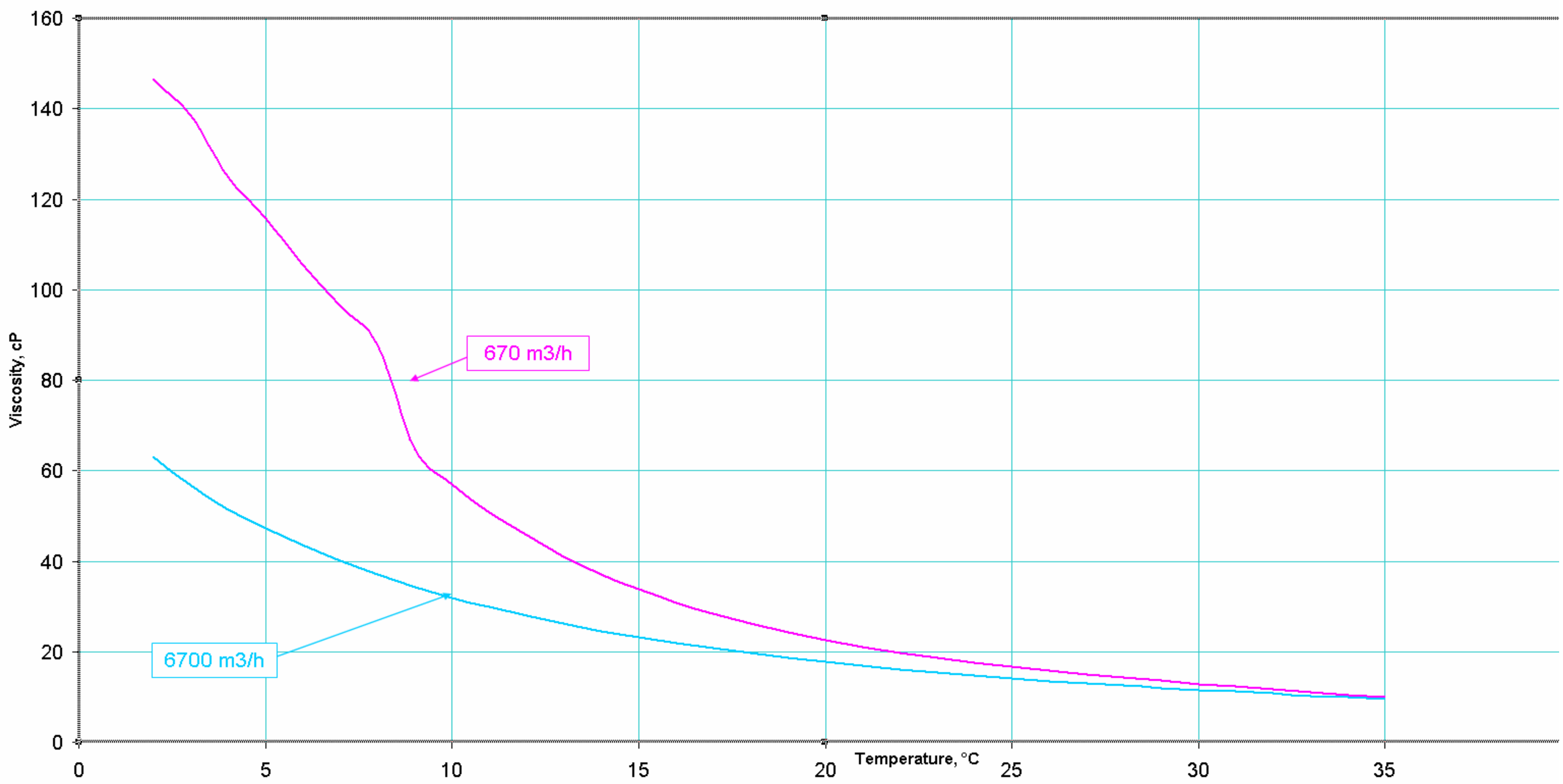

Figure 4-3 Viscosity of ACG Crude based on Effective Shear Rate Model vs. Temperature

μ , is the viscosity at P and T

VPMI is the pressure coefficient of viscosity; VTMI is the temperature coefficient of viscosity. The temperature coefficient is calculated as follows:

$$\mu = \mu_o\, e^{(VTMI \cdot \Delta T)} \tag{4-3}$$

$$\frac{\mu}{\mu_o} = e^{(VTMI \cdot \Delta T)} \tag{4-4}$$

$$VTMI = \frac{\ln \frac{\mu}{\mu_o}}{\Delta T} \tag{4-5}$$

Using the following values:

μ = 8.4cP at T_0= 35°C μ_o = 49cP at T = 5°C

VTMI equals:

$$VTMI = \frac{\ln \frac{8.4}{49}}{(35-5)} = -0.0588 \quad \frac{1}{{}^\circ C}$$

Similarly, the pressure coefficient is calculated as follows:

$$\mu = \mu_o\, e^{(VPMI \cdot \Delta P)} \tag{4-6}$$

$$\frac{\mu}{\mu_o} = e^{(VPMI \cdot \Delta P)} \tag{4-7}$$

$$VPMI = \frac{\ln \frac{\mu}{\mu_o}}{\Delta P} \tag{4-8}$$

To calculate the viscosity, μ , a second equation is used

$$\log \frac{\mu}{\mu_o} = \frac{P}{6895}(-0.0102 + 0.04042 \mu_o^{\ 0.181}) \tag{4-9}$$

Where, P is the pressure in kPa

Using the above equation for the following: constant temperature of 15°C, and μ_o = 22.9cP at P_o = 101.3kPa, the variable μ becomes 27.9cP at P = 10,000kPa. Solving Eq. 4-8,

$$VPMI = \frac{\ln\frac{27.9}{22.9}}{(10000 - 101.3)} = 0.00002\ {}^{1}\!/_{kPa} \tag{4-10}$$

Equation (4-2) can then be used to calculate the viscosity with the temperature and pressure effect and Figure 4-4 shows the variation in specific heat of the ACG crude oil with temperature.

Table 4.7 shows the basic fluid properties used in Stoner Model.

Table 4.7 Summary of Fluid Properties Used in Stoner Model

Property	Units	Value
Base pressure of this fluid	KPAA	101.32
Base temperature of this fluid	^oC	15
Base density of this fluid, i.e., density at P_0 and T_0	KG/M3	852
Bulk modulus at P_0 and T_0	KPA	1340000
Temperature modulus at P_0 and T_0	^oC	-1270
Multiplier for the DPDT term.		-9.7
Multiplier for the $(DP)^2$ terms.		9.5
Multiplier for the $(DT)^2$ terms.		1.15
Viscosity at P_0 and T_0	CP	22.9
Pressure coefficient of viscosity	1/KPA	0.00002
Temperature coefficient of viscosity	$1/^oC$	-0.05879
Heat capacity at constant density	KJ/KG-^oC	1.74
Temperature coefficient of heat capacity	KJ/KG-$^oC/^oC$	0
Heat conductivity at T_0	KJ/HR-M-^oC	0.446
Vapour pressure of the fluid at temperature T_1	KPAA	40.33
Temp. corresponding to the vapour pressure VP_1	^oC	15.56
Vapour pressure of the fluid at temperature T_2	KPAA	101.32
Temp. corresponding to the vapour pressure VP_2	^oC	37.78

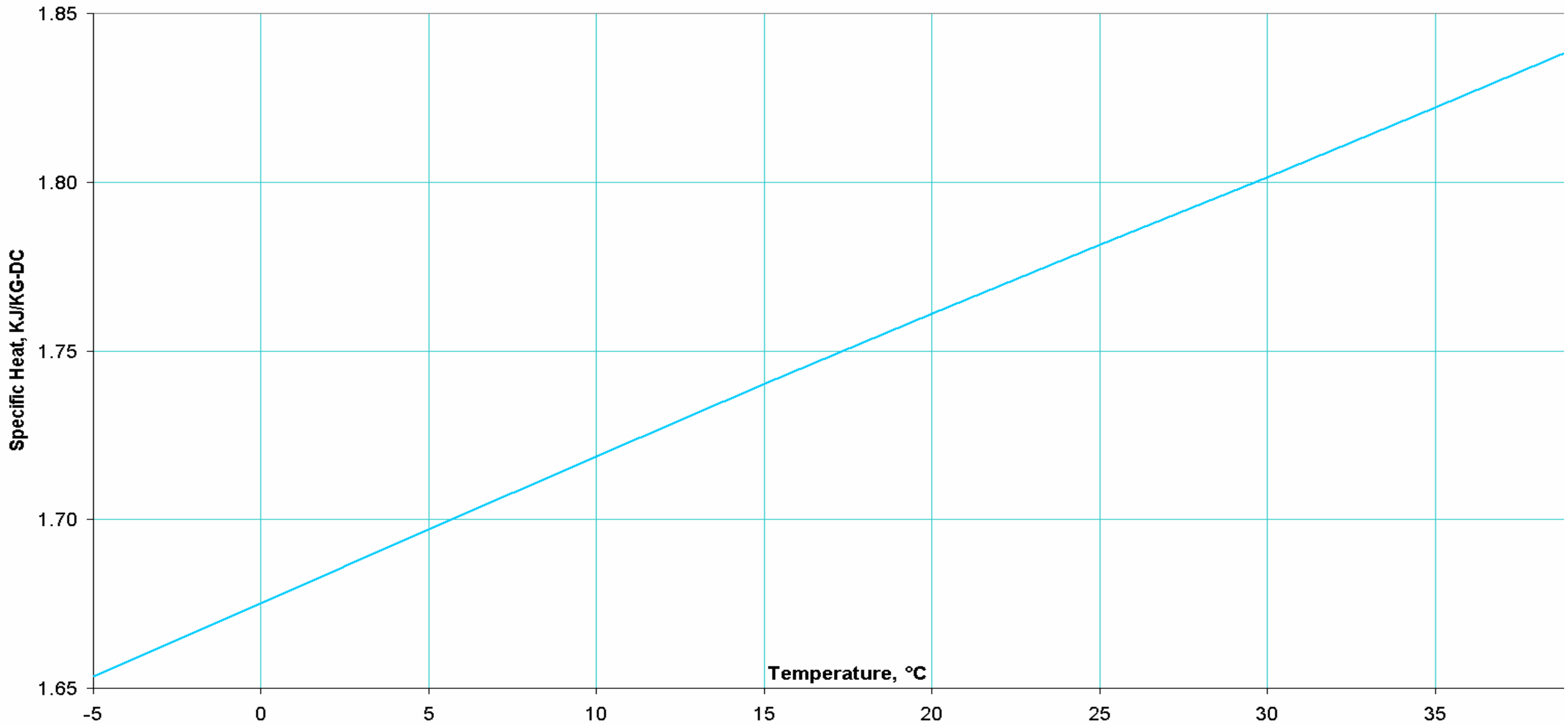

Figure 4-4 Specific Heat of ACG Crude vs. Temperature

4.3.2 Pipeline Production

The hydraulic design for the BTC System is based on an instantaneous maximum or peak hydraulic design capacity of 50 Million Ton Annual (MTA). For ACG crude oil, this equates to a peak hydraulic design flow rate of 6697 m^3/h. The minimum pipeline production is 5 MTA. The initial commitment for production build up is 25 MTA.

4.3.3 Pipeline Profile

The pipeline profile is shown in Figure 4-5.

4.3.4 Ground Temperature Variation

The maximum and minimum ground temperatures along the pipeline are shown in Figure 4-6, the minimum temperature values in the Stoner model simulation to establish the pumping requirements. The ground temperature profile is also shown in Figure 4-6. The Stoner program uses the ground surface temperature as input to estimate the liquid temperature in the pipe based on depth of cover.

The crude oil temperature variation along the pipeline is also shown in Figure 4-6. It shows that the temperature at the Georgia – Turkey border is 25°C.

4.3.5 Pipeline Block Valves

Block valves have been installed along the pipeline in order to stop the flow and reduce the amount of liquid discharged during pipeline breaks or ruptures. The location of the block valves is summarized below;

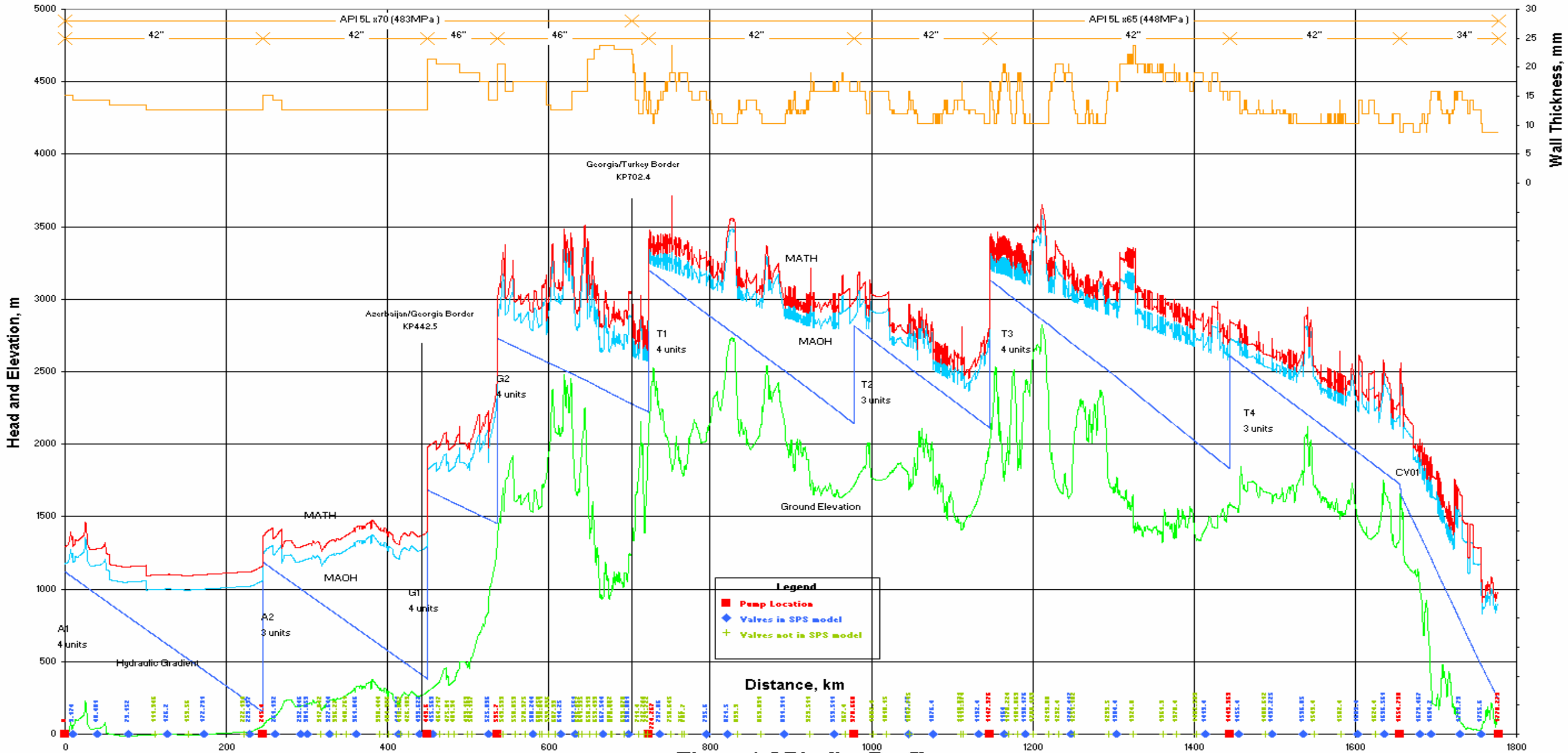

Figure 4-5 Pipeline Profile

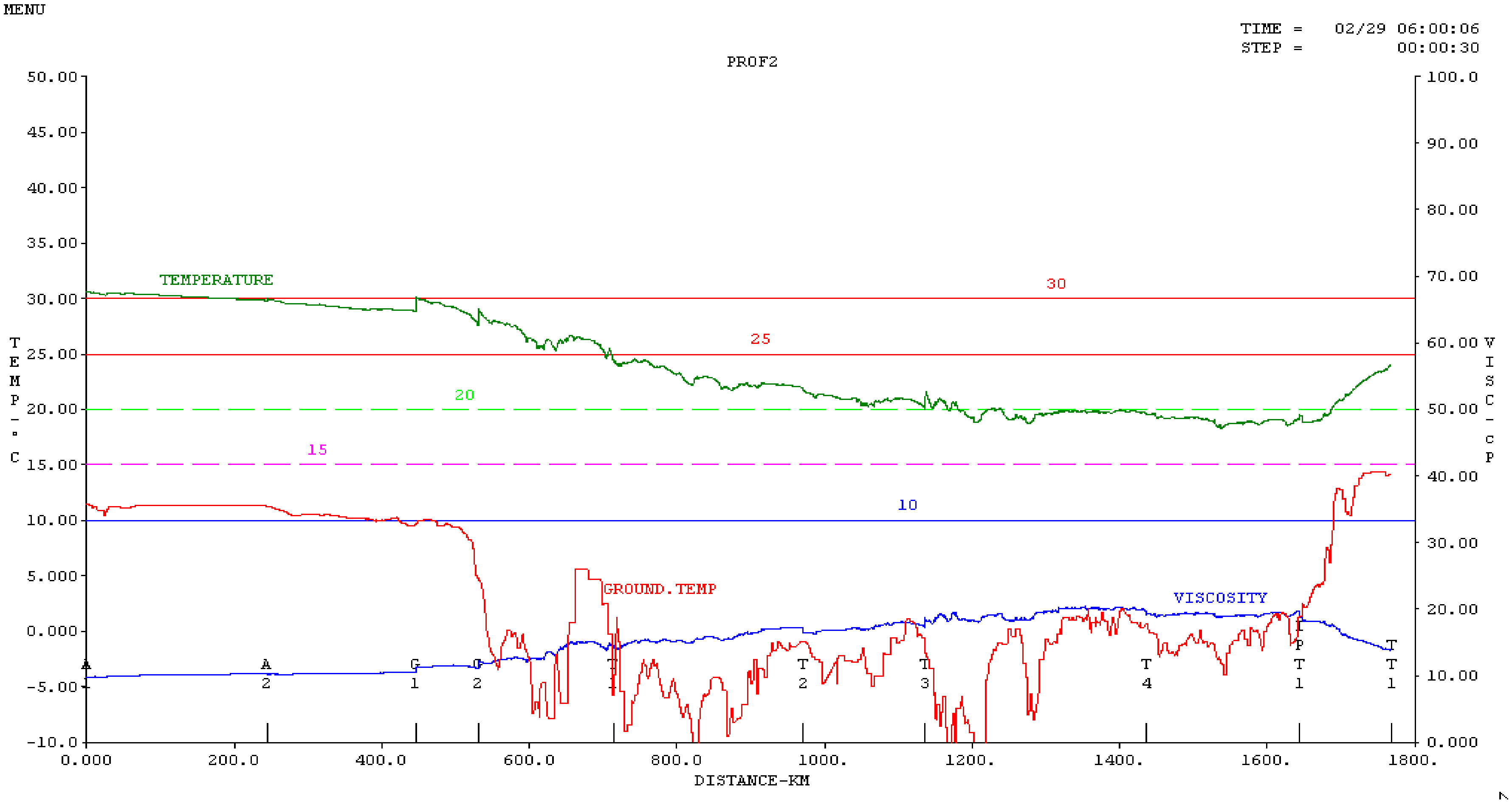

Fig 4.6 Ground and Oil Temperature Variation

Table 4-8 Location of In-line Block and Check Valve – Turkey Section

VALVE Name	Location km	Type of Valve	VALVE Name	Location, km	Type of Valve
BVT1	701.44	BALL	BVT27	1180.21	BALL
BVT2	707.778	BALL	BVT28	1190.137	BALL
BVT3	711.756	BALL	BVT29	1209.914	BALL
BVT4	727.094	BALL	BVT30	1222.434	BALL
BVT5	740.679	BALL	BVT31	1237.451	BALL
BVT6	755.034	BALL	BVT32	1241.216	BALL
BVT7	757.734	BALL	BVT33	1283.534	BALL
BVT8	785.634	BALL	BVT34	1294.434	BALL
BVT9	811.534	BALL	BVT35	1314.834	BALL
BVT10	823.934	BALL	BVT36	1351.934	BALL
BVT11	853.125	BALL	BVT37	1368.434	BALL
BVT12	881.345	BALL	BVT38	1392.543	BALL
BVT13	913.545	BALL	BVT39	1403.434	BALL
BVT14	943.545	BALL	BVT40	1445.434	BALL
BVT15	957.434	BALL	BVT41	1478.646	BALL
BVT16	992.434	BALL	BVT42	1487.259	BALL
BVT17	1008.184	BALL	BVT43	1526.084	BALL
BVT18	1035.464	BALL	BVT44	1539.434	BALL
BVT19	1037.749	BALL	BVT45	1572.434	BALL
BVT20	1066.434	BALL	BVT46	1593.434	BALL
BVT21	1100.355	BALL	BVT47	1614.434	BALL
BVT22	1103.408	BALL	BVT48	1626.595	BALL
BVT23	1122.434	BALL	BVT49	1669.501	BALL
BVT24	1154.034	BALL	BVT50	1684.234	BALL
BVT25	1160.258	BALL	BVT51	1719.764	BALL
BVT26	1171.097	BALL	BVT52	1745.634	BALL

Note: The valves in rows filled in grey colour are not included in the Stoner model

4.4 Design Flow Conditions

The design flow rate corresponding to 50 MTA production is 6700 m^3/h. The inlet temperature at Baku is assumed to be 30°C in all cases considered.

4.4.1 Base Case

The base case assumes a pipeline roughness of 0.1 mm from Baku to T1 and 0.0457 mm for the section from T1 to Ceyhan. The effect of pressure on oil viscosity is not considered. The pipeline profile and hydraulic gradient line at the design flow rate (6700 m^3/h) is shown in Figure 4-7. The pumping requirements are summarized in Table 4.9 The total mainline pumping power is estimated at 149,102 kW.

Table 4-9: Summary of Pumping Requirement at 6700 m^3/h

Pump Station	Flow/unit m^3/h	Temperature, ºC		Pressure, kPa		No of Units	Total Power kW
		Suction	Disch.	Suction	Disc.		
A1	1675	30.0	31.1	674	9320	4	18974
A2	2233	29.4	30.2	674	9368	3	18684
G1	1675	28.6	29.9	600	11582	4	24226
G2	1675	27.4	28.8	600	11327	4	23662
T1	1675	23.6	24.5	575	8800	4	17885
T2	6700	21.4	22.0	3400	9296	3	12525
T3	1675	20.0	21.0	575	9120	4	18657
T4	6700	19.2	19.9	1875	8652	3	14489
IPT1		19.4		3200	0		
TT1		24.9		1000			
					Total kW		149102

4.4.2 Minimum Flow

The minimum flow rate corresponding to 5 MTA production is 670m^3/h. The inlet temperature at Baku is assumed to be 30ºC. This case assumes a pipeline roughness of 0.1 mm from Baku to PS-T1 and 0.0457 mm for the section from T1 to Ceyhan. The effect of pressure on oil viscosity is included.

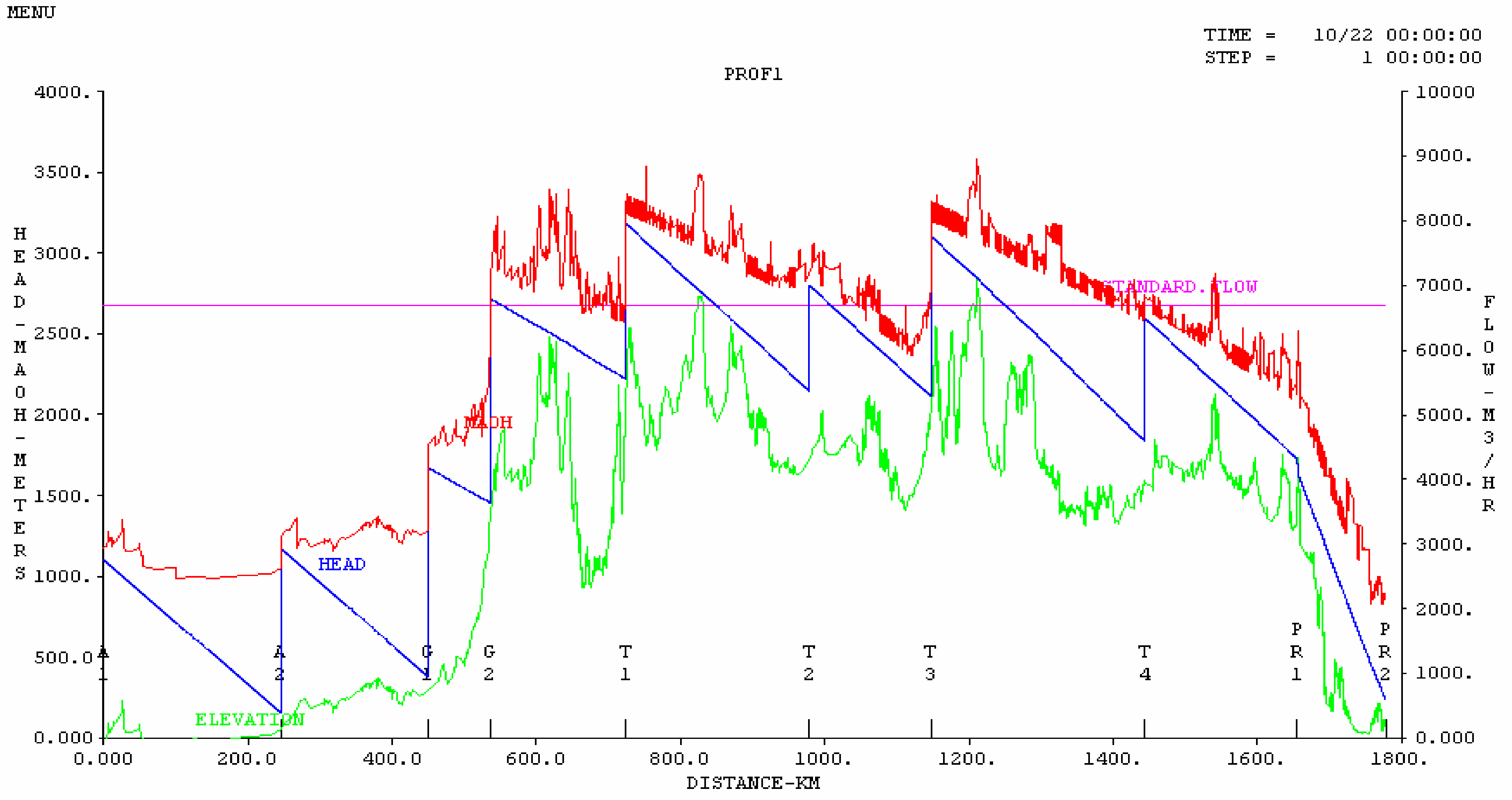

Figure 4-7 Pipeline Profile & Hydraulic Gradient at Design Flow Rate of 6700 m^3/h

The pumping requirements for this flow rate are summarized in Table 4.10. Total mainline pumping power is estimated at 8,806 kW in this case.

Table 4-10: Summary of Pumping Requirement at 670m^3/h

Pump Station	Flow/unit m^3/h	Temperature, ºC		Pressure, kPa		No of Units	Total Power kW
		Suction	Disch.	Suction	Disch.		
A1	670	30.0	30.4	798	3657	1	656
A2	0	25.0	25.0	2941	2941	0	0
G1	670	10.4	14.5	798	9798	1	2788
G2	670	9.9	13.9	723	9598	1	2745
T1	670	1.14	1.7	2997	5126	1	547
T2	0	-2.30	-1.0	7500	3574	0	0
T3	670	-2.13	1.3	697	6793	1	2070
T4	0	-0.05	1.0	7500	4542	0	0
IPT1		1.0		6000	0		
TT1		8.5		3400			
					Total, kW		8806

The minimum oil temperature drops to minus 4.7 degrees near km 896. The viscosity data for the oil at temperatures below 2 °C. are not available. These results should therefore be confirmed based on actual data that extend to minus 5°C. It should also be recognized that the oil may develop gel strength at low temperature.
The oil properties should therefore be examined in a pipe loop to confirm the flow properties of oil at low temperatures.

4.4.3 90 % Design Flow

The transient flow pumping requirements at 6030 m^3/h flow rate were estimated, Table 4.11. The inlet temperature at Baku is assumed to be 30°C. This case assumes a pipeline roughness of 0.1 mm from Baku to PS-T1 and 0.0457 mm for the section from PS-T1 to Ceyhan. The effect of pressure on oil viscosity is included.

Table 4-11 Summary of Pumping Requirement at 6030 m^3/h

Pump Sta-tion	Flow/unit m3/h	Temperature, oC		Pressure, kPa		No of Units	Total Power kW
		Suction	Disch.	Suction	Disch.		
A1	2010	30.0	31.1	697	8060	3	14894
A2	2010	28.4	29.2	697	8346	3	14773
G1	2010	26.9	28.3	623	11327	3	21228
G2	2010	25.6	26.9	623	10916	3	20453
T1	2010	21.3	22.3	748	2800	3	15529
T2	6030	18.6	19.2	4400	8725	2	8742
T3	2010	17.0	18.1	793	8992	3	16241
T4	6030	16.0	16.7	3100	7950	2	9897
IPT1		15.1		3800	0		
TT1		20.1		1000			
					Total, kW		121757

4.4.4 50 % Design Flow

The transient flow pumping requirements at 3350 m^3/h flow rate were estimated,Table 4.12. The inlet temperature at Baku is assumed to be 30°C. This case assumes a pipeline roughness of 0.1 mm from Baku to PS-T1 and 0.0457 mm for the section from T1 to Ceyhan. The effect of pressure on oil viscosity is included. Pump stations PS-A2, PS-T2 and PS-T4 are bypassed for this flow rate. The total pumping power is estimated at 41,691kW. The minimum temperature in the pipe was estimated to be 3.7ºC.

Table 4-12 Summary of Pumping Requirement at 3350 m^3/h

Pump Station	Flow/unit m3/h	Temperature, oC		Pressure, kPa		No of Units	Total Power kW
		Suction	Disch.	Suction	Disch.		
A1	1675	30.0	30.9	767	7745	2	7688
A2	0	23.8	23.8	4775	4775	0	0
G1	1675	19.4	20.6	693	10334	2	10691
G2	1675	17.5	18.8	693	10068	2	10415
T1	1675	11.4	12.1	2168	6548	2	4988
T2	0	7.0	7.0	7001	7001	0	0
T3	1675	5.0	6.0	668	7747	2	7909
T4	0	4.5	4.5	7501	7501	0	0
IPT1		5.0		5000	0		
TT1		8.0		1000			
					Total, kW		41691

4.4.5 30 % Design Flow

The transient flow pumping requirements at 2010 m^3/h flow rate were estimated, Table 4-13. The inlet temperature at Baku is assumed to be 30 ºC. This case assumes a pipeline roughness of 0.1 mm from Baku to PS-T1 and 0.0457 mm for the section from T1 to Ceyhan. The effect of pressure on oil viscosity is included.

Pump stations PS-A2, PS-T2 and PS-T4 are bypassed for this flow rate. The total pumping power is estimated at 22,029 kW. The minimum temperature in the pipe was estimated to be 1.3ºC below zero.

Table 4-13: Summary of Pumping Requirement at 2010 m^3/h

Pump Station	Flow/unit m3/h	Temperature, ºC		Pressure, kPa		No of Units	Total Power kW
		Suction	Disch.	Suction	Disch.		
A1	2010	30.0	30.9	787	5124	1	3180
A2	0	20.0	20.0	3578	3578	0	0
G1	2010	14.9	16.3	712	10003	1	6244
G2	2010	13.1	14.4	712	9693	1	6062
T1	2010	5.9	6.5	2587	5510	1	2097
T2	0	1.5	1.5	7001	7001	0	0
T3	2010	0.2	1.3	687	7053	1	4446
T4	0	1.0	1.0	7501	7501	0	0
IPT1		1.5		5500	0		
TT1		5.1		1000			
					Total, kW		22029

CHAPTER 5

TRANSIENT FLOW CASE STUDIES

5.1 Cases

Transient hydraulic calculations that have been carried out for the load cases can be summarized as follows:

- failure of pumping stations,
- closure of control valves and
- closure of a block valve

5.2 Selection of Transient Events

Any disturbance of a steady state condition creates a transient event or pressure surges.

Possible disturbances might comprise the following points:

- Scheduled or unscheduled shut-off valve closure during operation

  An unscheduled closure of valves is prohibited by mechanical and electronic measures. Unscheduled closure is only possible in case of multiple failures. In case of a scheduled valve closure the operators have to consider preconditions for block valve closure which reduce the risk.

  The closing time of the valves was selected to avoid risks.
- Scheduled or unscheduled flow / pressure control valve closures

  An unscheduled control valve closure caused by malfunction of the equipment cannot be avoided.

  Upstream of all control valves, pressure relief systems are installed which protect the system and avoid overpressures.

- Scheduled and unscheduled pump shutdown

  An unscheduled pump trip by power failure cannot be avoided.

  Scheduled pump shutdown leads to less critical pressure since the pumps are shut down in case of hydraulically favourable conditions.

  Upstream of each pumping station, pressure relief systems are installed which protect the system from overpressures.
- Scheduled system shutdown;

  During a scheduled shutdown overpressures in the system are avoided by hydraulically optimised time points for pump shutdown or set point changes. During the shutdown the current hydraulic conditions are continuously monitored.
- Scheduled system start-up;

  During a scheduled start-up overpressures in the system are avoided by hydraulically optimised time points for pump start or set point changes. During the start-up the current hydraulic conditions are continuously monitored.
- Safety measures in case of System Control and Data Acquisition (SCADA) failures;

  SCADA failures have a slim possibility but can occur.

  Special station safety sequences (SSS) execute a hydraulically optimised system shutdown.
- Scheduled closure of Block Valves in case of a pipeline leak;

  In case of a pipeline rupture (leak) high flow rates occur in the pipeline. It is to be checked if the block valves can be closed with pressures remaining inside the allowed limits.

5.3 Computation Time for Cases

Each case is computed until a new steady state condition is reached and/or that relief valves which are checked are closed again. Since the drain-down or fill-up effect in the slack line sections is to be considered the computation time in some cases is extremely long.

5.4 MAOP and 10% Overpressure Line on Plot

The MAOP of the pipeline and the 10% overpressure line (acc. to ANSI B31.4) shown on the printouts of the computation results is based on the wall thickness distribution.

5.5 System Description of Transient Events

5.5.1 Pipeline

The pipe is API 5L Grade X-65 with specified minimum yield strength (SMYS) of 4483 MPa (65000 psi). The maximum allowable operating pressure (MAOP) is based on pipe stress equal to 72 percent of SMYS. The maximum allowable transient pressure (MATP) is 10% above the MAOP as per ASME B31.4.

5.5.2 Pipeline Valves

Block valves and check valves have been provided along the pipeline. There are 23, 26 and 52 such valves in Azerbaijan, Georgia and Turkey sections of the pipeline, respectively. The locations of these valves are given in Table 5-1.Out of 101 mainline valves, 34 valves was selected for analysis using Stoner model. The valves are consecutively numbered in the Stoner model as MLV01 through MLV35. The locations of the selected valves are also given in Table 5-1.

Table 5-1: Location of Pipeline Main Valves

Azerbaijan – Georgia Section				Turkey Section			
AZ-Ge		Stoner Model		As Built		Stoner Model	
Valve #	km	MLV #	km	Valve #	Km	MLV #	km
1	9.174	1	9.174	BVT01	9.000		
2	40.481	2	40.481	BVT02	15.344		
3	79.152	3	79.152	BVT03	19.322		

Table 5-1: Location of Pipeline Main Valves-(Continued)							
Azerbaijan – Georgia Section				Turkey Section			
AZ-Ge		Stoner Model		As Built		Stoner Model	
Valve #	**km**	**MLV #**	**km**	**Valve #**	**Km**	**MLV #**	**km**
4	111.946			BVT04	34.660	17	737.0
5	126.200	4	126.200	BVT05	48.245		
6	153.560			BVT06	62.600		
7	172.791	5	172.791	BVT07	65.300		
8	222.194			BVT08	93.200		
9	229.457	6	229.457	BVT09	119.100	18	821.5
10	261.132	7	261.132	BVT10	131.500		
11	292.146	8	292.146	BVT11	160.691		
12	301.053	9	301.053	BVT12	188.911	19	891.3
13	317.012			BVT13	221.111		
14	327.644	10	327.644	BVT14	251.111	20	953.5
15	336.270			BVT15	265.000		
16	348.761			BVT16	300.000		
17	361.046			BVT17	315.750		
18	390.444			BVT18	343.030	21	1045.
19	401.386			BVT19	345.315		
20	414.071			BVT20	374.000	22	1076.
21	416.092			BVT21	407.921		
22	426.109			BVT22	410.974		
23	439.622	11	439.622	BVT23	430.000	23	1132.
24	455.563			BVT24	461.600	24	1164.
25	464.717			BVT25	467.824		
26	475.010			BVT26	478.663		
27	481.940			BVT27	487.776		
28	499.169			BVT28	497.703		
29	504.137			BVT29	517.480		

Table 5-1: Location of Pipeline Main Valves-(Continued)							
Azerbaijan – Georgia Section				Turkey Section			
AZ-Ge		Stoner Model		As Built		Stoner Model	
Valve #	**km**	**MLV #**	**km**	**Valve #**	**Km**	**MLV #**	**km**
30	525.036	12	525.036	BVT30	530.000		
31	543.599			BVT31	545.017	25	1247.
32	558.059			BVT32	548.782		
33	570.375			BVT33	591.100		
34	580.244			BVT34	602.000	26	1304.
35	589.158			BVT35	622.400		
36	590.641			BVT36	659.500		
37	599.096			BVT37	676.000		
38	607.930			BVT38	700.109		
39	614.250	13	614.250	BVT39	711.000	27	1413.
40	632.561	14	632.561	BVT40	753.000	28	1455.
41	636.452			BVT41	786.212		
42	641.395			BVT42	794.825		
43	650.919			BVT43	833.650	29	1536.
44	659.439			BVT44	847.000		
45	667.544	15	667.544	BVT45	880.000		
46	676.052			BVT46	901.000	30	1603.
47	678.440			BVT47	922.000		
48	693.078			BVT48	934.161	31	1636.
49	698.881	16	698.881	BVT49	977.067	32	1679.
				BVT50	991.800		
				BVT51	1027.33	33	1729.
				BVT52	1053.20	34	1755.

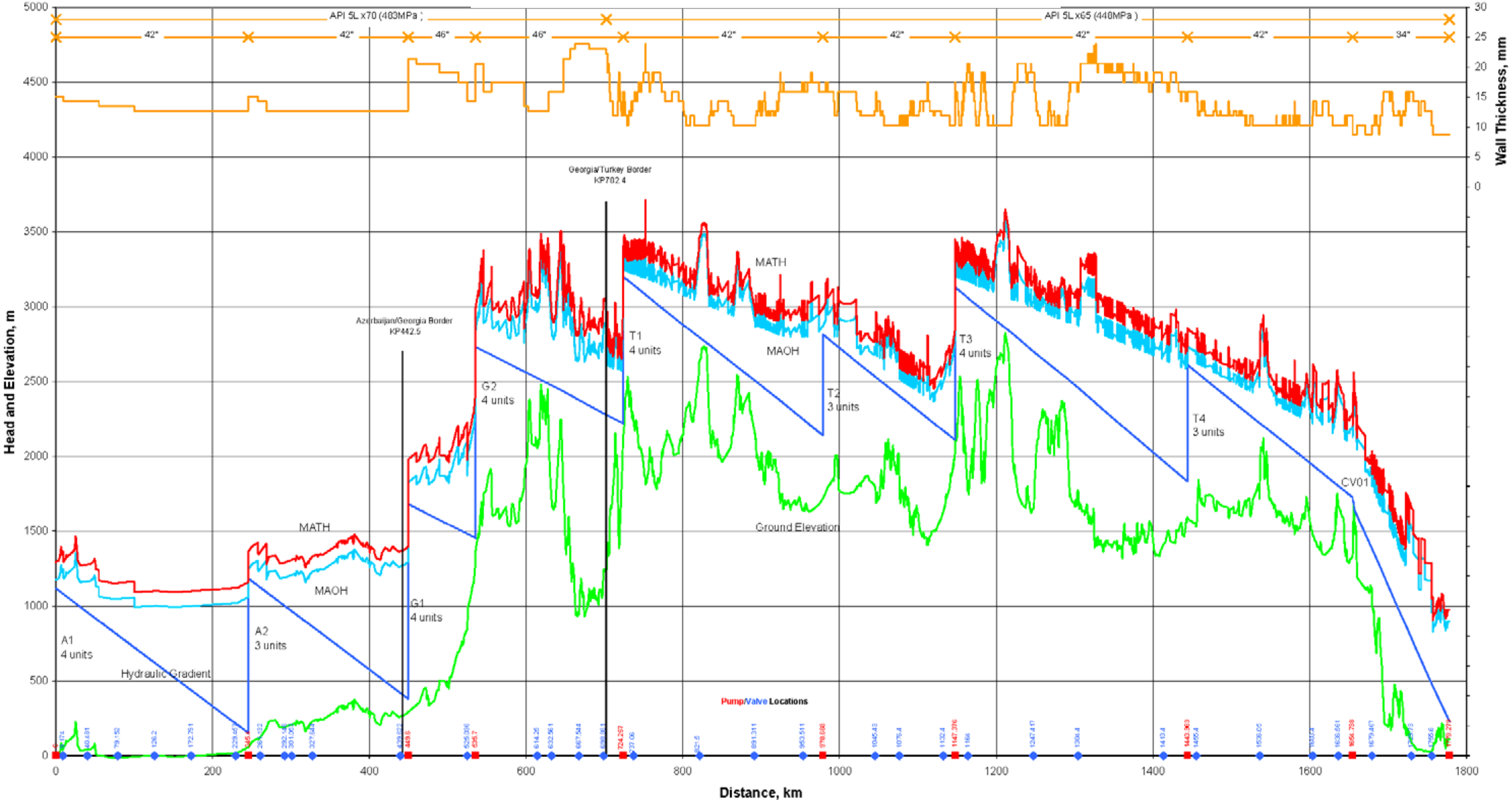

Figure 5.1 Hydraulic Gradient Line of the Entire Pipeline

5.6 Case Studies

The following general and some important specific cases are examined in this study and recommendations are given based on the results;

- Pump Station Shutdown- ICSS Operational
- Pump Station Shutdown -Ssytem Shutdown in 15 Minutes
- Transients due to One Pump Trip
- Transients due to Block Valve Closure-ICSS Operational
- Transients due to Block Valve Closure-ICSS is not Operational
- Maximum Transient Pressure due to Block Valve Closure
- Pipeline Rupture
- Impact of PS-A1 Shutdown on Booster Pump Station
- Start-Up of Pump Station A2
- Pipeline Shutdown and Start Up
- Normal Shutdown
- Emergency Shutdown
- Normal Start Up
- Station SSD-System Shutdown in 2 Minutes
- Pump Station PS-G1 Shutdown
- ESD of Ceyhan
- Surge due to Block Valve Closure-ICSS Operational
- Maximum Transient Pressure due to Block Valve Closure
- Simulation of Rupture

5.6.1 Pump Station Shutdown- ICSS Operational

When Integrated Control and Scada System, (ICSS) in the Az/Ge section is operational the two immediately upstream pump stations are shutdown in 2 minutes following a shutdown or an Emergency Shut Down (ESD) at a pump station. The other upstream pump stations are shutdown in a similar fashion. The upstream pump station shutdown following detection of a Pump Station shutdown should be initiated by ICSS. For the Turkey section the upstream pump stations are shutdown in 2 minutes by ICSS system in that section.

The transient pressures remain within acceptable limits for this scenario.

5.6.2 Pump Station Shutdown -Sytem Shutdown in 15 Minutes

The transients due to pump station ESD when the ICSS is not operational were examined. It assumes that ESD or System Shut Down, (SSD) occurs soon after ICSS at the pump station fails. When ICSS failure to a pump station occurs, the immediately upstream pump station will be shutdown in 15 minutes by the ICSS system.

For these scenarios, it was assumed that the upstream pump stations are shutdown 15 minutes after the start of closure of ESD valves or pump station SSD. The maximum transient pressures were found to be acceptable for ESD as well as SSD at all eight pump stations. The relief volume is maximum under these scenarios and is used for sizing relief tanks.

5.6.3 Impact of In-Line Check Valves

In the event of unplanned pump station shutdown or accidental closure of block valves, the transient pressures remain within acceptable limits even when in-line check valves with a closing time of 100 milliseconds is present.

5.6.4 Transients due to One Pump Trip

When an operating pump at a pump station trips then the ICSS will start the standby pump if the station is in automatic mode of operation and the standby pump is ready. The analysis indicated that the transients due to one pump trip at a given pump sta tion followed by start-up of standby pump after 10 minutes does not give rise to significant change in pipeline flow rate. However, restart of the standby pump within 10 minutes is not critical. The system operates at a lower flow rate when the standby pump fails to start.

5.6.5 Transients due to Block Valve Closure-ICSS Operational

The transients caused by accidental valve closure for block valve between pump stations in the Az/Ge section were examined. When the ICSS system is operational, the upstream pump stations are shutdown 2 minutes after the detection of the start of block valve closure. The maximum transient pressures remained within allowable limits.

The effectiveness of the relief systems installed on bypass of valves BVT036, 39, 49 and 52 in the Turkey section was confirmed using Stoner model. The upstream pump station shutdown following detection of block valve closure should be initiated by ICSS.

5.6.6 Transients due to Block Valve Closure-ICSS is not Operational

When the ICSS system is not available at a mainline block valve in the Az/Ge section, the system flow rate as well as discharge pressure controller set points are reduced to a safe value one minute after it is confirmed that ICSS to the valve is lost. This action should be part of ICSS.

Closure of a valve in Turkey section is likely produce transient pressures that exceed static pressure at the valve location. The Turkey section has not been designed to take full static head in some pipe sections between PS-T2 and Intermediate Pigging Station1 (IPT1) and will over pressure the pipe. For this analysis it is assumed that all upstream pump stations are shutdown within one minute following loss of ICSS to a mainline block valve in the Turkey section.

5.6.7 Maximum Transient Pressure due to Block Valve Closure

When there is communications failure to a mainline block valve in the Az/Ge section of the pipe, the flow rate and discharge pressure controller set points are reduced to safe flow levels. If the flow and discharge pressure set points are not reduced then the maximum transient pressures may exceed the allowable pressures. The maximum transient pressures under these conditions were estimated for selected mainline block valves. These valves are farthest from a pump station and were selected in other scenarios that gave higher transient pressures. Valves closer to the pump station have not been analysed.

The estimated maximum transient pressures due to closure of selected mainline block valves are summarized in Table 5.2

Table 5.2: Summary of Maximum Transient Pressures due to Mainline Valve Closure

Valve	Location, km	Maximum Transient Pressure as SMYS %
AB08	227.42	90
AB22	435.65	90
GB05	495.51	Below MAOP (MOP)
BVT003	711.87	92

5.6.8 Re-Injection From Relief Tanks at PS-G1

The re-injection of oil from relief tanks at PS-G1 was simulated. When one of the tanks is empty, the flow rate in section upstream of PS-G1 could be increased to 6600 m^3/h while the re-injection pump is pumping 100m^3/h at PS-G1.

When both relief tanks at PS-G1 are full (a number of consecutive relief events), the ICSS will not permit start-up of the upstream pump stations. If this lockout is overridden in order to start operation, the maximum flow rate between pump stations PS-

A1 and PS-G1 must be reduced to 40 percent of the design flow rate in order to prevent relief system activation at PS-G1 in case of PS-G1 trip.

5.6.9 Pipeline Rupture

Transient pressures resulting from full line size rupture at ten selected locations were analysed. The upstream pump station is shutdown by operators following detection of rupture. The mainline block valves in the section of pipe in which the rupture is located are also closed by the operator.

Immediately after the rupture, the flow rate becomes very high (20000 to 70000 m^3/h) and then it starts to decrease with time. The maximum transient pressures were found to be within acceptable limits.

5.6.10 Impact of Transient Flow on Flush Pump

The impact of transient flow on the operation of the flush pump was investigated. Transient created by PS-G1 trip while pipeline is operating in bypass mode was used for analysis. The pumps at PS-A1 were assumed to operate until they are shutdown 15 minutes after activation of relief system at PS-G1.

The flush pumps will experience maximum pressure equal to the maximum transient pressure at the location of the flush pump on suction side. The discharge side would be subject to 20 bar higher pressure. The flush pump may be shutdown on high pressure in order to keep the same design pressure for suction and discharge side of the pump. A high discharge pressure pump trip switch has been provided to protect the pump.

5.6.11 Impact of Valve Leakage

If the PS-G2 main pump check valve leaks but the discharge valve does not leak then reverse flow stops after 1 minute and the maximum transient pressures exceed MOP in some sections between PS-G1 and PS-G2. The pressures remain below MATP throughout the pipeline.

5.6.12 Discharge Pressure Controller and Trip Set Points

The mainline pump discharge pressure trip set points are 150 kPag above the discharge pressure controller set points for the Az/Ge section of the pipe. A margin of 200 kPag between the discharge pressure controller set point and the trip set points has been used for the Turkey section.

It was desirable to establish maximum acceptable values for the trip and discharge pressure controller set points to determine if larger margin between the controller set points and trip set points can be achieved for the first four pump stations. The analysis indicated that the margin between the discharge pressure controller set point and trip set point can be increased provided that a higher MAOP is determined from the hydro tests. The recommended set point values provide a margin of about 500 kPag between operating pressure at design flow and the trip set point. It is recommended that the pump station trip set points are set 500 kPag above the individual pump trip points.

5.6.13 Discharge Pressure Trip Command Failure

Surge due to failure of high discharge pressure mainline pump trip command was examined to determine if it could result in pipe failure when a mainline block valve closes or pump station trips or an ESD occurs at a pump station and the upstream pump stations fail to shutdown.

It should be noted that these are not realistic scenarios. The closure time of suction ESD valves was reduced to 20 seconds in order to obtain higher transient pressures.

The maximum hoop stress resulting from transient pressures for all cases examined were found to be less than SMYS and pipe failure under these scenarios is not expected. The maximum transient pressures for the scenarios examined are summarized in Table 5.3

Table 5.3 Summary of Maximum Transient Pressures Scenarios[2]

PS-A2 Shutdown	Below Potential MAOP
PS-G1 Shutdown	Below Potential MATP
PS-G2 Shutdown	Below Potential MATP
PS-T1 Shutdown	Below Potential MAOP
ESD Valve at PS-A2 suction Closes	85% of SMYS
ESD Valve at PS-G1 suction Closes	Below Potential MATP
ESD Valve at PS-G2 suction Closes	Below Potential MATP
ESD Valve at PS-T1 suction Closes	Below Potential MAOP
Block Valve AB22 Closes	86% of SMYS
Block Valve GB05 Closes	Below Potential MATP
Block Valve BVS003 Closes	97.6% of SMYS
Block Valve BVS003 Closes in 4 minutes	97.6% of SMYS

5.6.14 Selection of Number of Operating Pumps

The number of operating mainline and booster pumps should be such that flow through individual pump remains within the maximum and minimum flow rate lim

[2] For all Scenarios the upstream pump stations continue to operate and the trip switches are inactivated. The discharge pressure controller set point is 150 kPag below MAOP of the pipe downstream of the pump station. The mainline block valve closure time is 7 minutes while the ESD valve closure time is 20 seconds.

its. Each mainline pump is provided with a recycle valve that opens when the pump flow drops to minimum flow at a given speed. Recycle valve control logic should perform this function. The number of operating pumps is selected based on target flow rate and established duty order of each pump at a pump station.

5.6.15 Impact of PS-A1 Shutdown on Booster Pump Station

A number of scenarios were examined to evaluate the impact of mainline pump trip at PS-A1 on the surge pressures at the booster pump station. The maximum transient pressures were found to exceed MATP of the valves and fittings designed according to ASME B31.3 in some of the cases examined. A relief valve set to open at a pressure of 1945 kPag was considered for protecting the booster pump station against over pressure. An 8-inch and a 10-inch relief valves were examined for the cases with no leak through the mainline check valves. The results indicated that a 10-inch relief valve is needed to keep the maximum transient pressures below 133% of MAOP.

5.6.16 Start-Up of Pump Station A2

Pump Station A2 (PS-A2) is bypassed when the pipeline flow rate is 3884 m^3/h of less. The pressure at PS-A2 is about 5300 kPag when it is operating in bypass mode at a flow rate of 3884 m^3/h. Start-up of PS-A2 while the pipeline is operating in bypass mode must be carried out in accordance with the defined procedure since the pump differential head available is zero just prior to the start-up PS-A2 and the suction pressure may be higher than allowable pressure limit. Initially the flow rate at PS-A1 is reduced in order to reduce pressure at PS-A2. Transient analysis was performed with flow reduction at PS-A1 in order to stay within the allowable operating limits of PS-A2 mainline pumps.

The recommended safe flow rates and discharge pressure controller set points for block valves in Az/Ge section are given in Table 5.4

Table 5.4 Safe Flow Rate & Discharge Pressure Controller Set Points

Item	Valve Location			
	PS-A1 To PS-A2	**PS-A2 To PS-G1**	**PS-G1 To PS-G2**	**PS-G2 To PS-T1**
Safe Flow, % of design	**85**	**75**	**100**	**30**
Pump Station	**Discharge Pressure Controller Set Point, kPag**			
A1	7350	6135	9550	5150
A2	7660	6700	9500	Bypass
G1	10890	10640	11800	9990
G2	10865	10650	11800	9650
T1	8255	7550	9100	5550
T2	7910	7125	9300	Bypass
T3	8955	8720	9550	7040
T4	7450	6970	8950	Bypass

5.7 Pipeline Shutdown and Start Up

Simulations using Stoner model were performed to examine the hydraulic conditions developed during pipeline shutdown and start up. For shutdown cases, the initial pipeline flow rate is 6700 m^3/h.

5.7.1 Normal Shutdown

Normal pipeline shutdown should be carried out in a sequential manner in order to reduce or eliminate relief at pump stations in the Turkey section. The hydraulic condition after shutdown is shown in Figure 5.2. Relief systems were not activated. The shutdown sequence should be confirmed during pipeline commissioning.

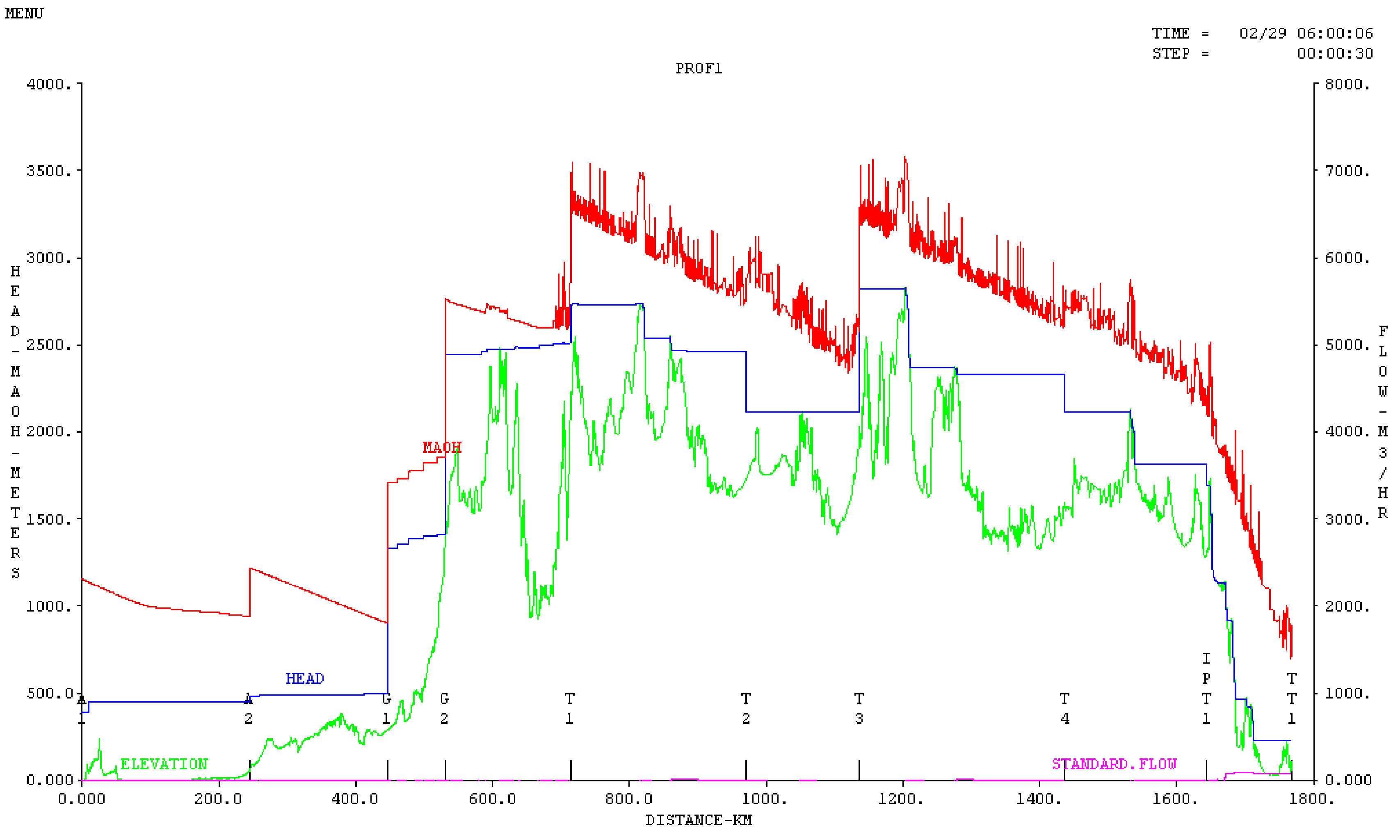

Figure 5.2 Normal Shutdown

5.7.2 Emergency Shutdown

If there is an emergency, the whole pipeline may be shutdown immediately. All operating pumps are shutdown at time zero. In order to reduce relief volume, the pump station bypass valves at PS-T2 and T4 are closed after some time and the discharge pressure controllers are activated. The IPT1 suction pressure is raised and if necessary the Ceyhan valve is closed.

Relief occurs at various pump stations during an emergency shutdown. Figure 5.3 shows variation in cumulative volume of oil relieved at various locations. The relief volumes remain within the capacity of the relief tanks if the station bypass valves at PS-T2 and T4 are closed as indicated. The variation in relief system flow rate with time is shown in Figure 5.4.

5.7.3 Normal Start Up

Pipeline start-up following a short duration shutdown was simulated. The simulation indicated that the pipeline can be started in about one hour. The start up sequence should be confirmed during pipeline commissioning.

5.8 Station SSD-System Shutdown in 2 Minutes

When a pump station shutdown (SSD) or emergency station shutdown (ESD) is detected by ICSS, the two immediately upstream pump stations will be shutdown using the ISD logic at those stations. The shutdown of the upstream pump stations in turn will trigger shutdown in other upstream pump stations until all upstream pump stations are shutdown. For the purpose of analysis a delay of 2 minutes between detection of SSD (or ESD) and all upstream pump station shutdowns has been used.

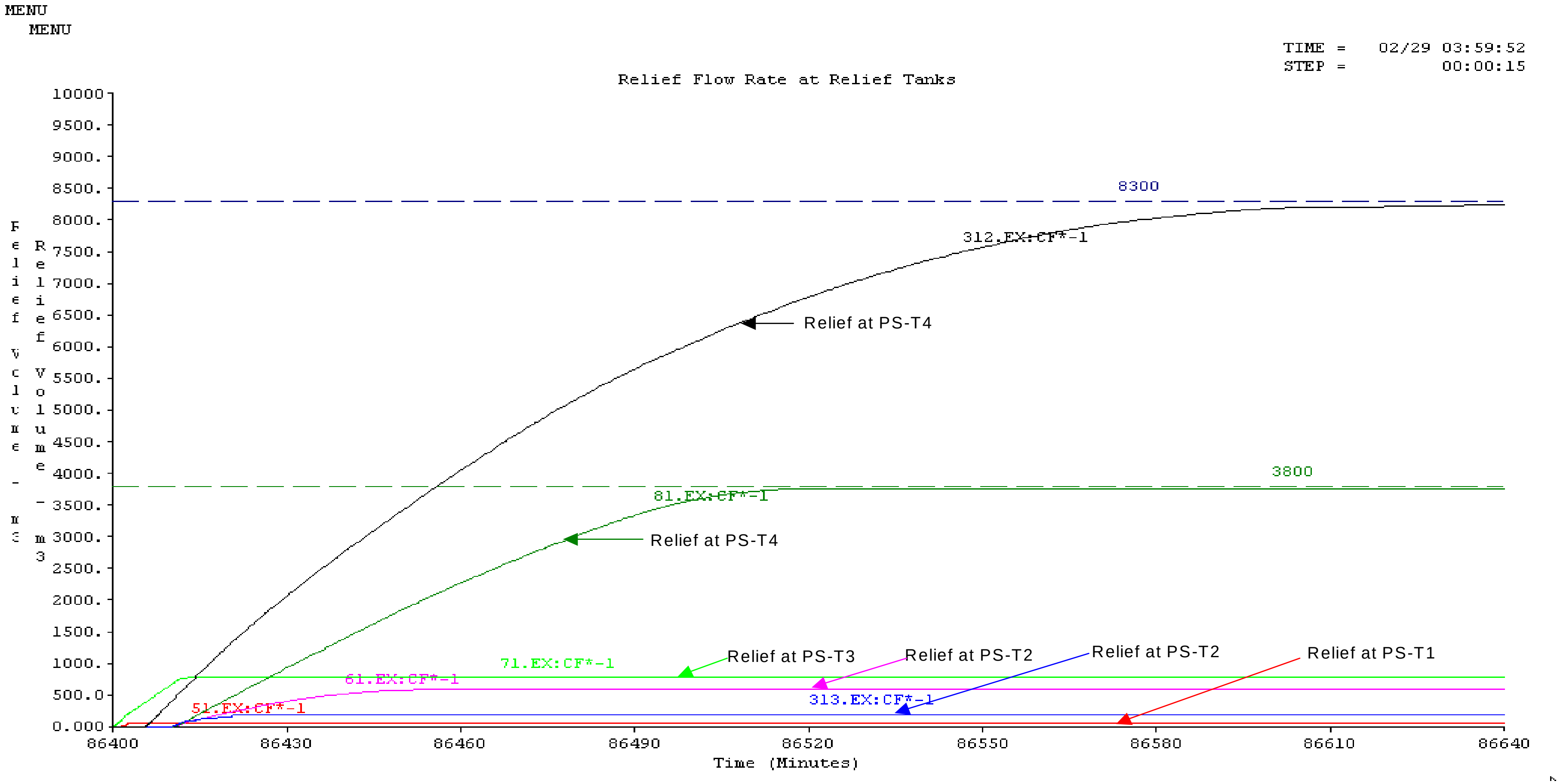

Figure 5.3 Cumulative Volume Relieved During Emergency Shutdown

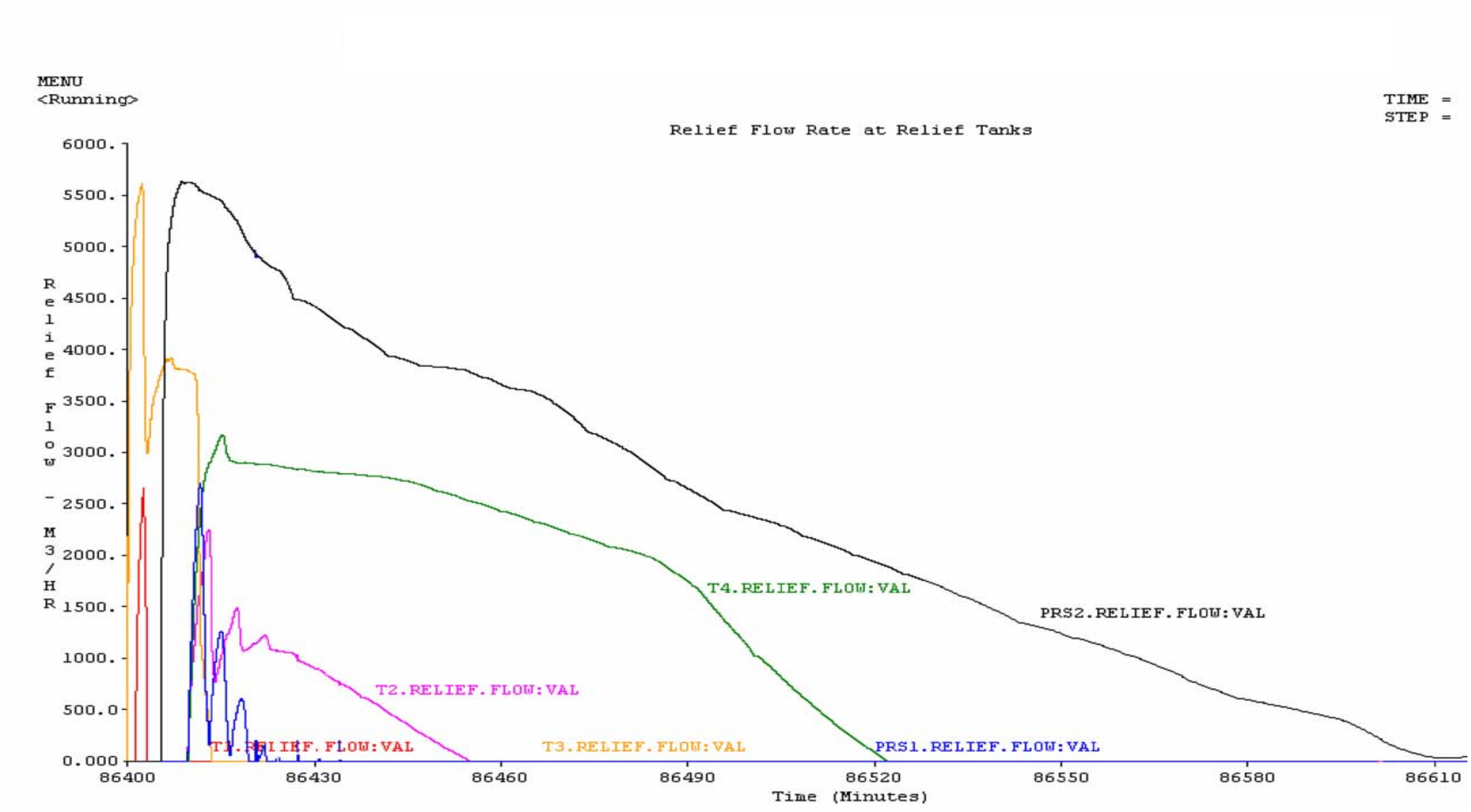

Figure 5.4 Variation in Relief System Flow rate During Emergency Shutdown

5.8.1 Pump Station PS-G1 Shutdown

This scenario assumes that the pipeline is initially operating in steady state at the design flow rate of 6700 m^3/h. There is an emergency valve closure at pump station PS-G1. The ICSS and Telecommunications system are available. The pipeline is shutdown using ICSS system. ICSS triggers shutdown of two immediately upstream pump stations, within 2 minutes after an ESD or SSD occurs at a pump station.

5.8.1.1 Shutdown Sequence

The sequence of events is summarized in Table 5.5.

Table 5.5: Shutdown Sequence

Time, minutes	Action
0	Stop Pumps 3P01, 3P02, 3P03 and 3P04 at PS-G1.
2.	Shutdown all of the operating pumps at the upstream stations simultaneously[3]

5.8.1.2 Simulation Results

The pipeline profile and pressure variation at 5, 10, 15, 30 and 60 minutes after PS-G1 shutdown are shown in Figure 5.5. The maximum pressure envelope along the first 720 km of the pipeline is also shown in this figure. This figure shows that the maximum transient pressure does not exceed MAOP anywhere in the pipeline.

[3] In all simulations the shutdown of upstream pump stations is assumed to be simultaneous. The ICSS shuts down the immediately upstream two stations that in turn shutdown two other upstream stations and so on until the system is shutdown.

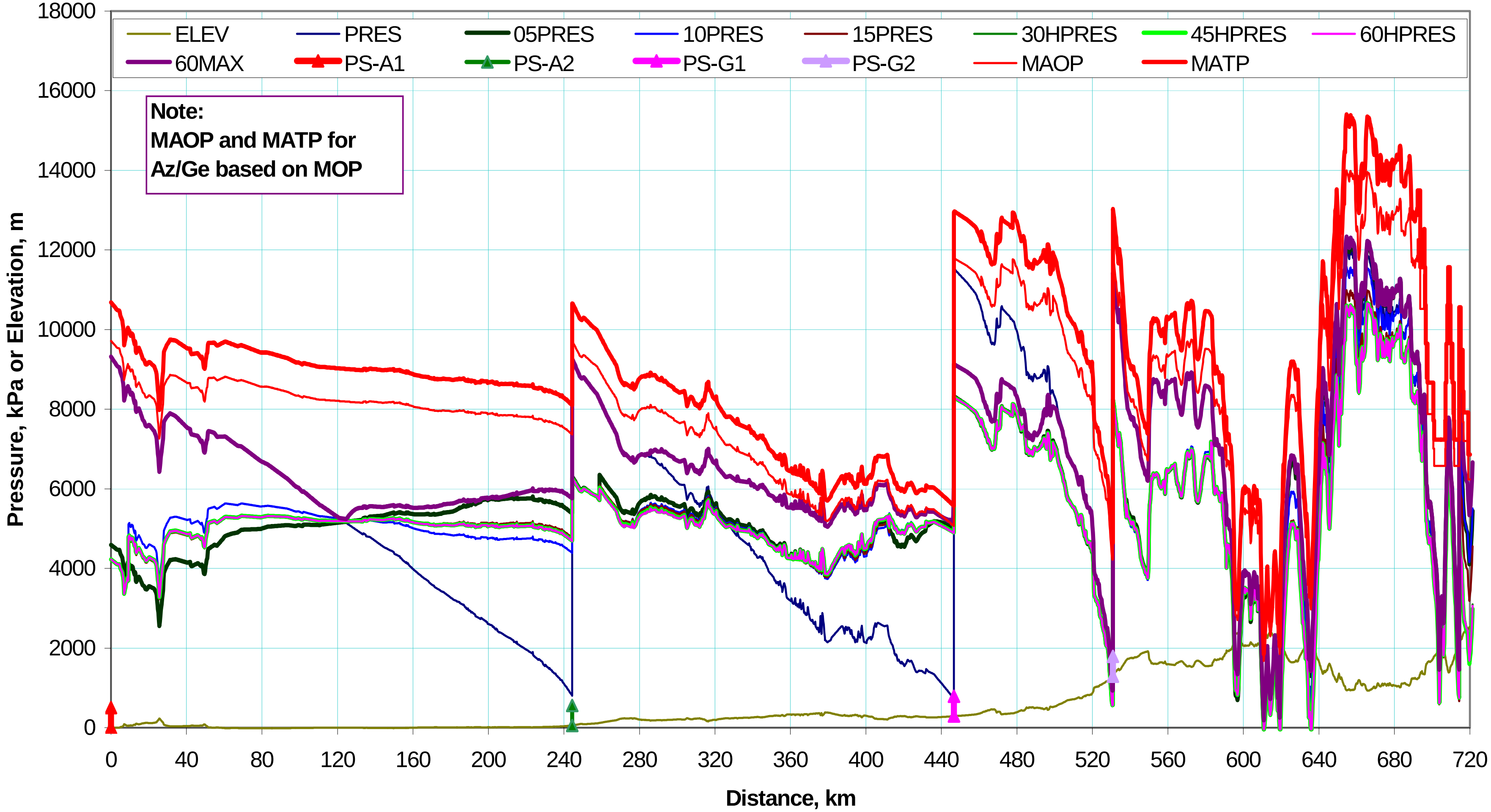

Figure 5.5 Pressure Variation along Pipeline 2 Minutes after Shutdown of PS-G1

The relief system at PS-G1 is activated during shutdown of the system. The variation in flow rate and cumulative flow with time is shown in Figure 5.6. This figure shows that the flow through the relief systems stops in about 3 minutes. The total amount of crude oil released through the relief systems at PS-G1 was estimated to be about 100 cubic meters. This is 8% of the relief tank capacity at PS-G1. The maximum flow through the relief system was found to be 3400 m^3/h.

5.8.2 Pump Station PS-G2 Shutdown

This scenario assumes that the pipeline is initially operating in steady state at the design flow rate of 6700 m^3/h. The operating pumps at pump station PS-G2 trip. The ICSS and Telecommunications system are available. The pipeline is shutdown using ICSS system.

5.8.2.1 Shutdown Sequence

The sequence of events is summarized in Table 5.6

Table 5.6: Shutdown Sequence

Time, minutes	Action
0	Stop Pumps 4P01, 4P02, 4P03 and 4P04 at PS-G2.
2.	Shutdown all of the operating pumps at the upstream stations simultaneously

5.8.2.2 Simulation Results

The pipeline profile and pressure variation at 5, 10, 15, 30 and 60 minutes after PS-G2 shutdown are shown in Figure 5.7. The maximum pressure envelope along the

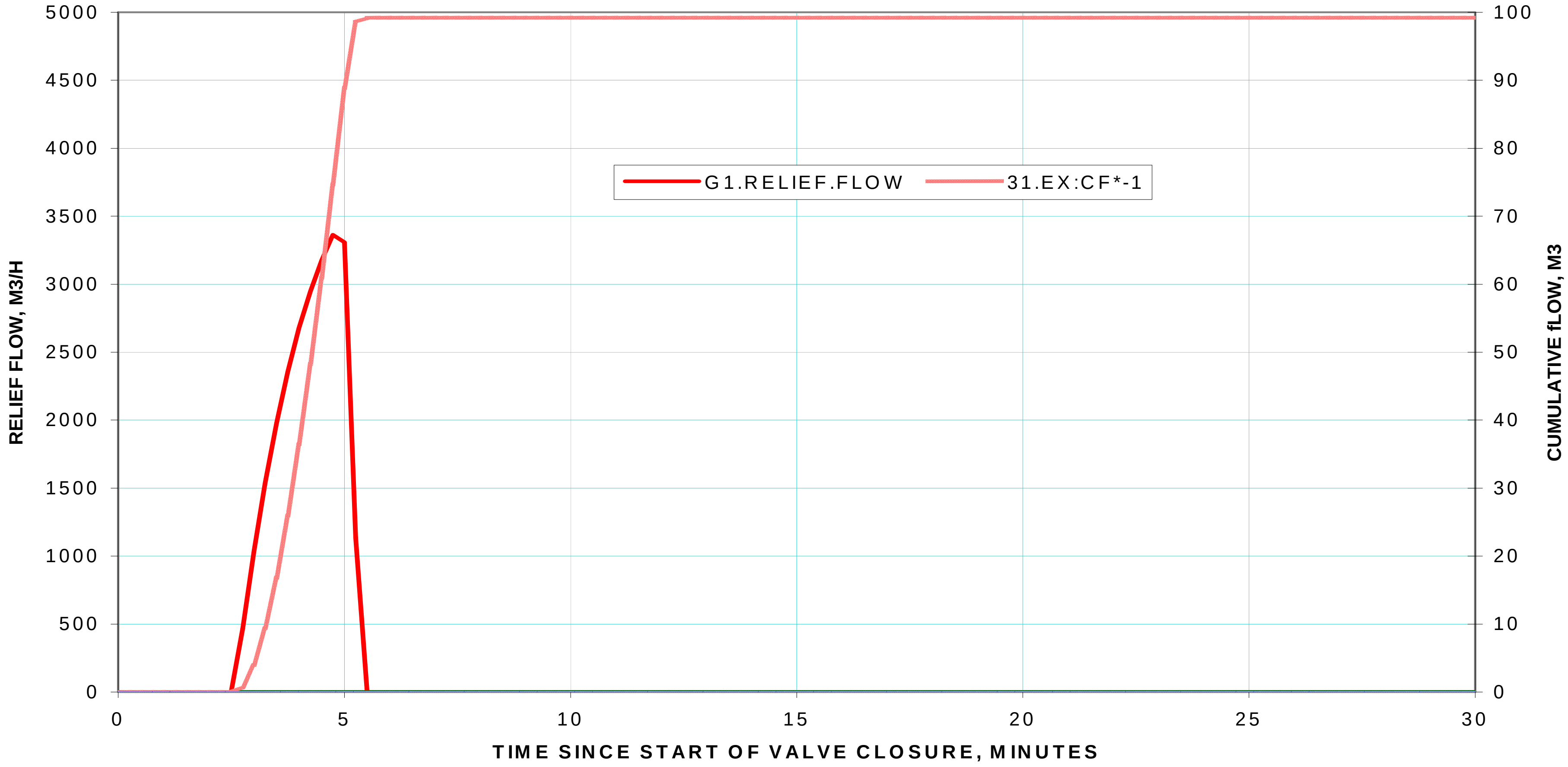

Figure 5.6 Relief Systems 2 Minutes After Shutdown of PS-G1

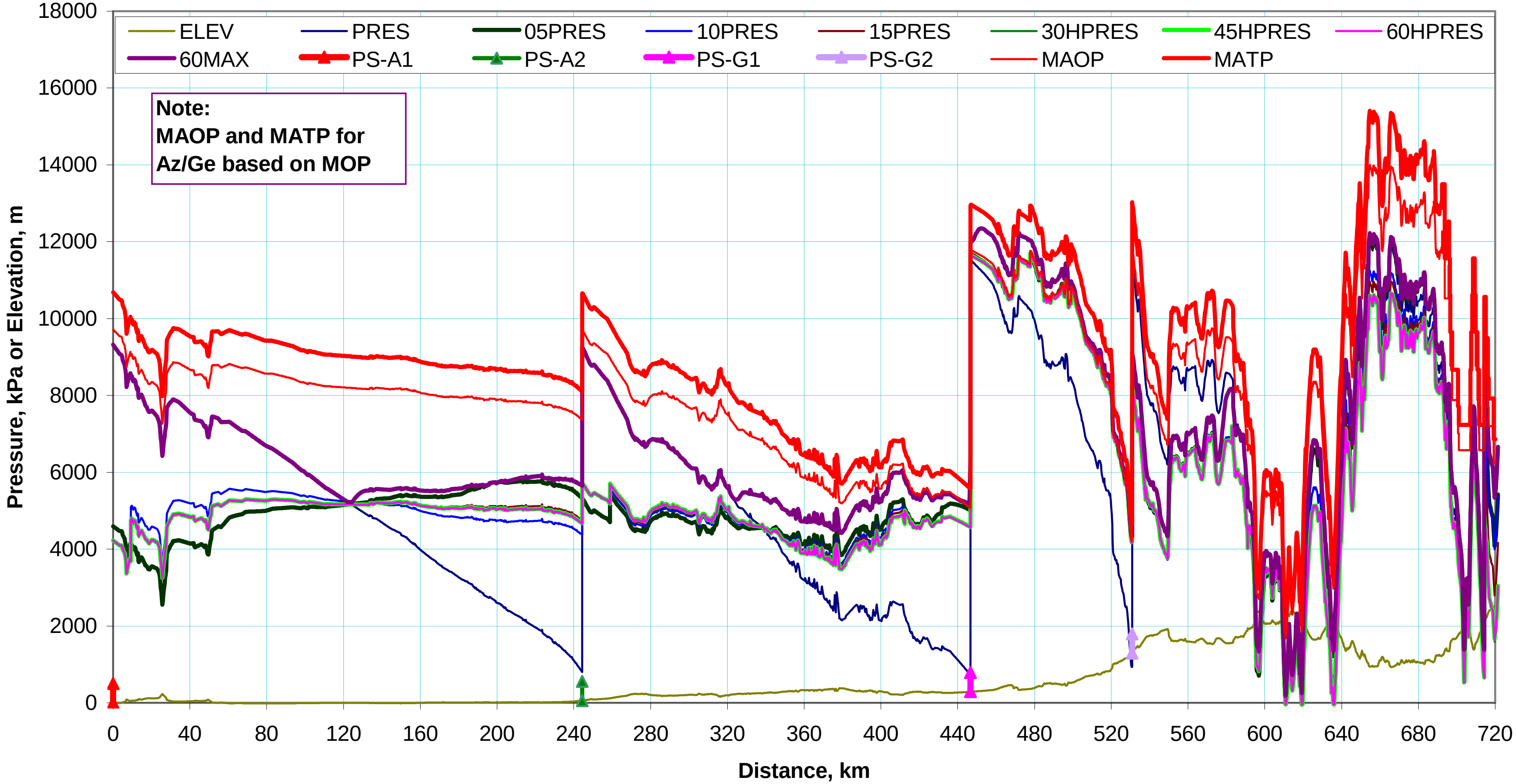

Figure 5.7 Pressure Variation along Pipeline 2 Minutes after Shutdown of PS-G2

first 720 km of the pipeline is also shown in this figure. This figure shows that the maximum transient pressure does not exceed MAOP anywhere in the pipeline.

The relief system at PS-G1 is activated during shutdown of the system. The variation in flow rate and cumulative flow with time is shown in Figure 5.8. This figure shows that the flow through the relief systems stops in about 2 minutes.

The total amount of crude oil released and maximum flow rate through the relief system at PS-G1 were estimated to be about 32 cubic meters and 2200 m^3/h respectively.

5.8.3 ESD of PS-T1

This scenario assumes that the pipeline is initially operating in steady state at the design flow rate of 6700 m^3/h. The operating pumps at pump station PS-T1 trip. The ICSS and Telecommunications system are available.

5.8.3.1 Shutdown Sequence

The sequence of events is summarized in Table 5.7

Table 5.7: Shutdown Sequence

Time, minutes	Action
0	Stop Pumps 5P01, 5P02, 5P03 and 5P04 at PS-T1.
2.	Shutdown all of the operating pumps at the upstream stations simultaneously
Various	Follow the procedure for normal shutdown for remaining system

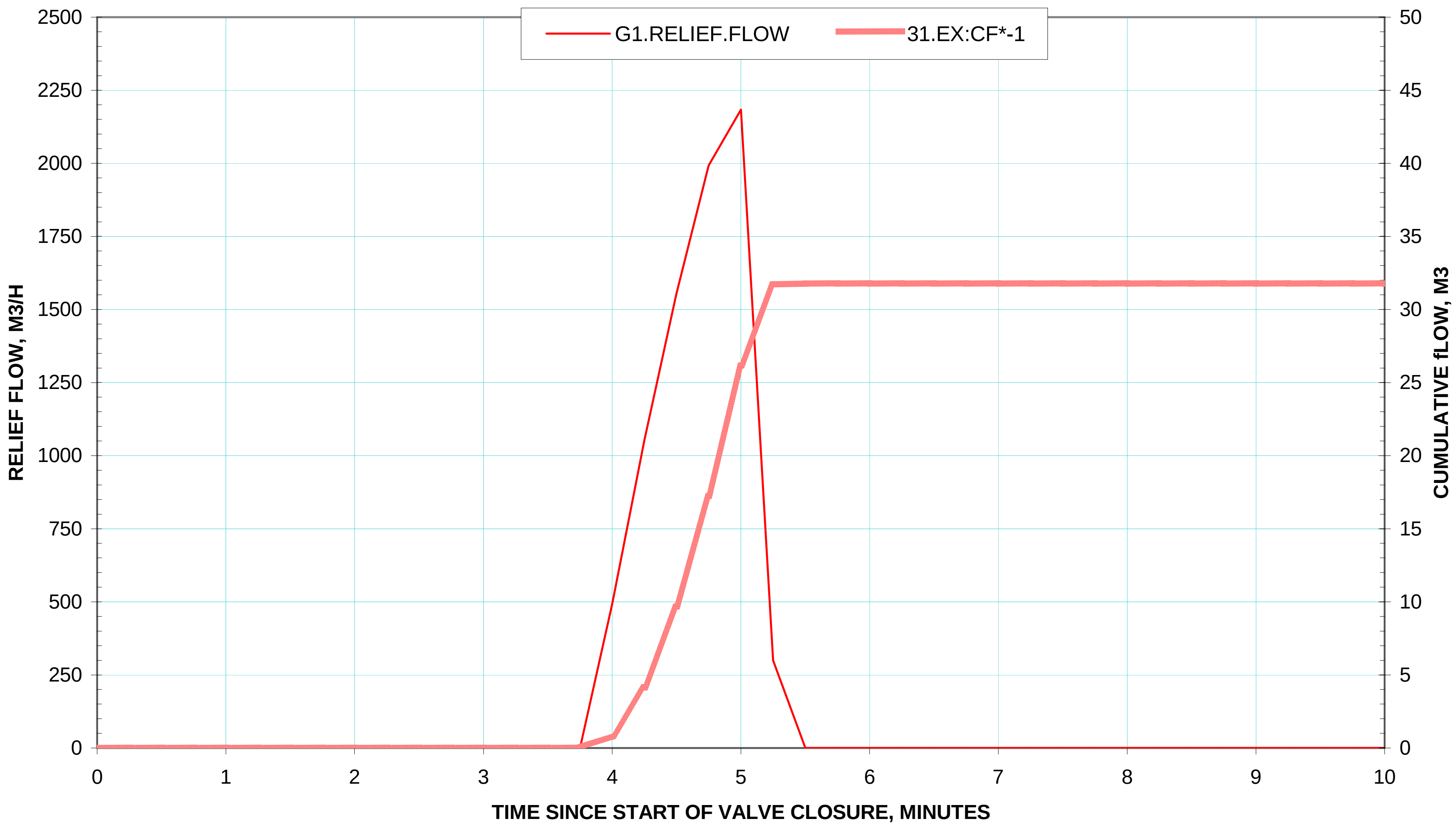

Figure 5.8 PS-G2 Relief System 2 Min. After Upstream Shutdown

5.8.3.2 Simulation Results

The pipeline profile and pressure variation at 5, 10, 15, 30 and 60 minutes after PS-T1 shutdown are shown in Figure 5.9. The maximum pressure envelope along the first 720 km of the pipeline is also shown in this figure. This figure shows that the maximum transient pressure does not exceed MAOP anywhere in the pipeline.
The relief systems at PS-G1 and PS-T1 are activated during shutdown of the system. The variation in flow rate and cumulative flow with time for the relief systems is shown in Figure 5.10. This figure shows that the flow through the relief systems stops in less than 1 minute at PS-G1 and about 5 minutes at PS-T1.

The total amount of crude oil released through the relief systems at PS-G1 and PS-T1 were estimated to be about 6 and 175 cubic meters respectively. The maximum flow rates through the relief systems at PS-G1 and PS-T1 were estimated to be 880 and 4100 m^3/h respectively

5.8.4 ESD of Ceyhan

This scenario assumes that the pipeline is initially operating in steady state at the design flow rate of 6700 m^3/h. The flow controller at Ceyhan accidentally closes. The ICSS and Telecommunications system are available.

5.8.4.1 Shutdown Sequence

The sequence of events is summarized in Table 5.8

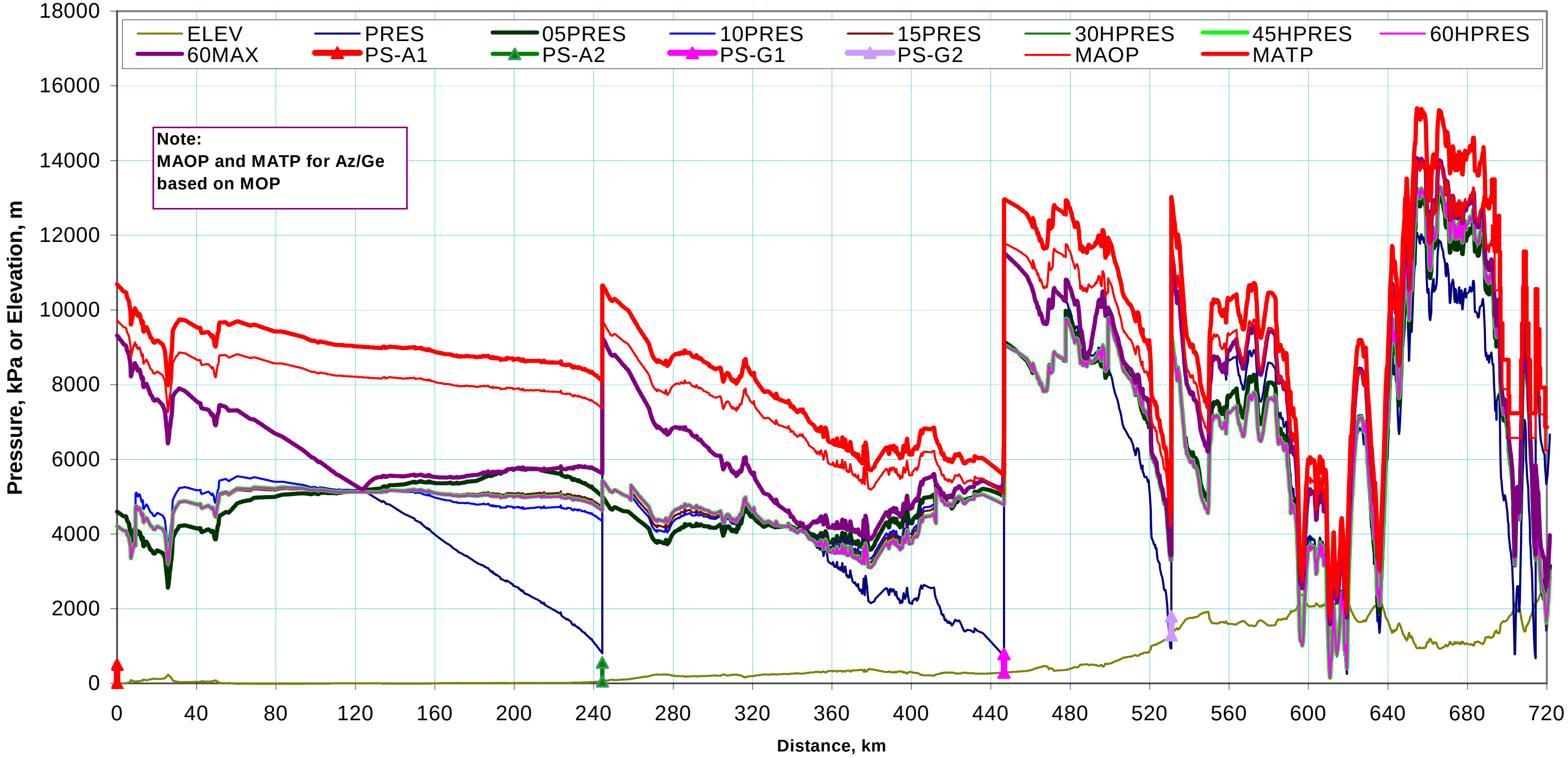

Fig 5.9 Pressure Variation along Pipeline 2 Minutes after Shutdown of PS-T1

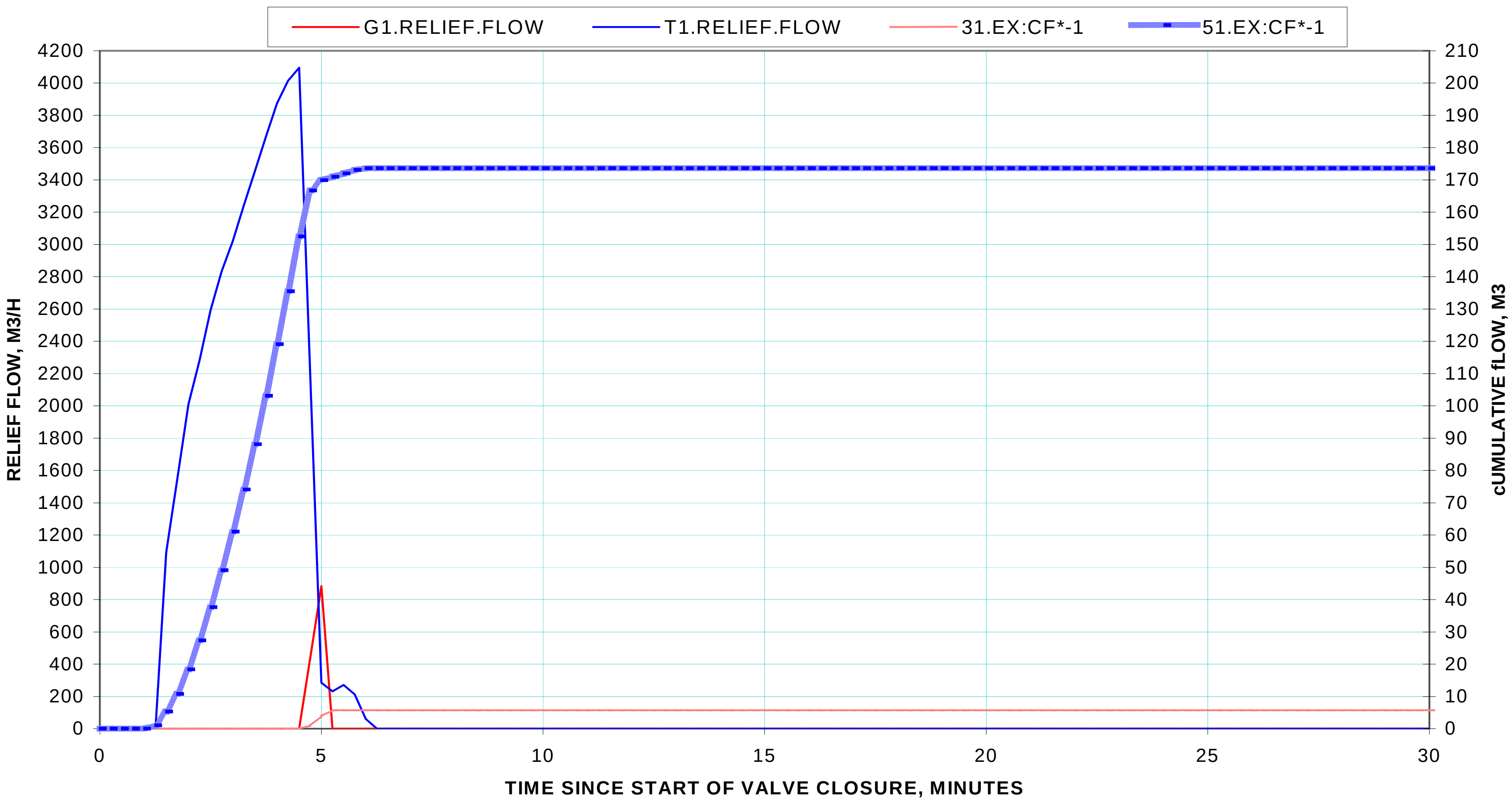

Figure 5.10 Relief Systems 2 Minutes After Shutdown of PS-T1

Table 5.8: Shutdown Sequence

Time, minutes	Action
0	Control Valve at Ceyhan closes completely by accident.
2.	Shutdown all of the operating pumps at the upstream stations simultaneously The valve at IPT1 is closed

5.8.4.2 Simulation Results

The maximum transient pressure envelope between km 1350 and Ceyhan is shown in Figure 5.11. This figure shows that the maximum transient pressure does not exceed MAOP anywhere in the pipeline.

The relief systems at PS-T1, T2, T3, T4, IPT1 and Ceyhan are activated during shutdown of the system. The variation in flow rate and cumulative flow with time for the relief systems are shown in Figures 5.12 and 5.13 respectively. The total amount of crude oil released through the relief systems at various locations was estimated to be less than the volume of one relief tank at that location.

5.8.4.3 Conclusions and Recommendations

The transient pressures resulting from an SSD at a pump station in the Az/Ge section of pipe were found to remain below MAOP of the pipeline when the upstream pump stations are tripped within 2 minutes by the ICSS.

An ESD at a pump station in then Az/Ge section immediately shuts down the mainline pumps and therefore the impact of ESD will be the same as that of SSD. The control philosophy for Az/Ge section is to shutdown the two immediately upstream pump station when an SSD or ESD is detected at a pump station.

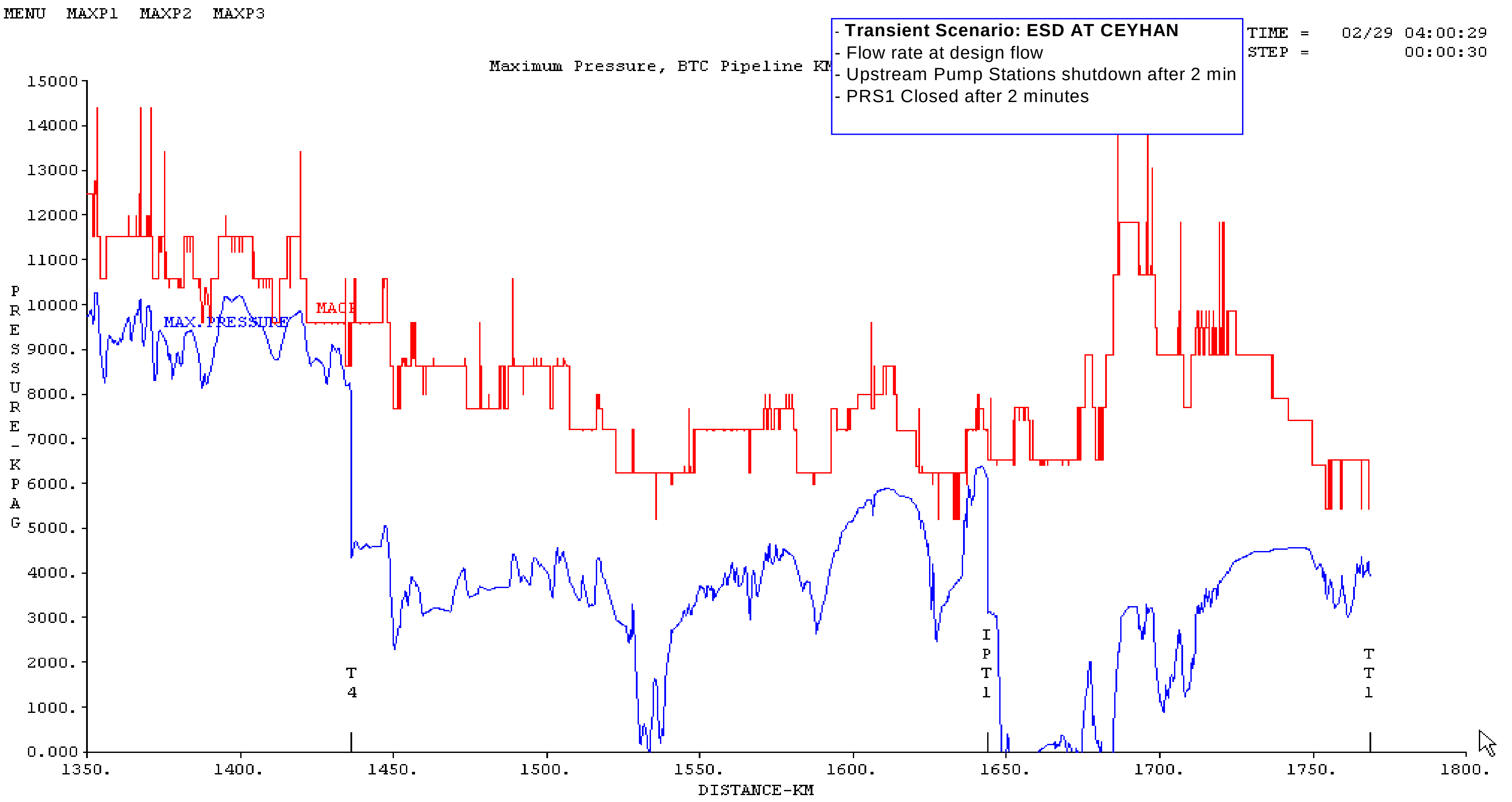

Figure 5.11 Maximum Transient Pressure Variation Between km 1350 and Ceyhan Terminal

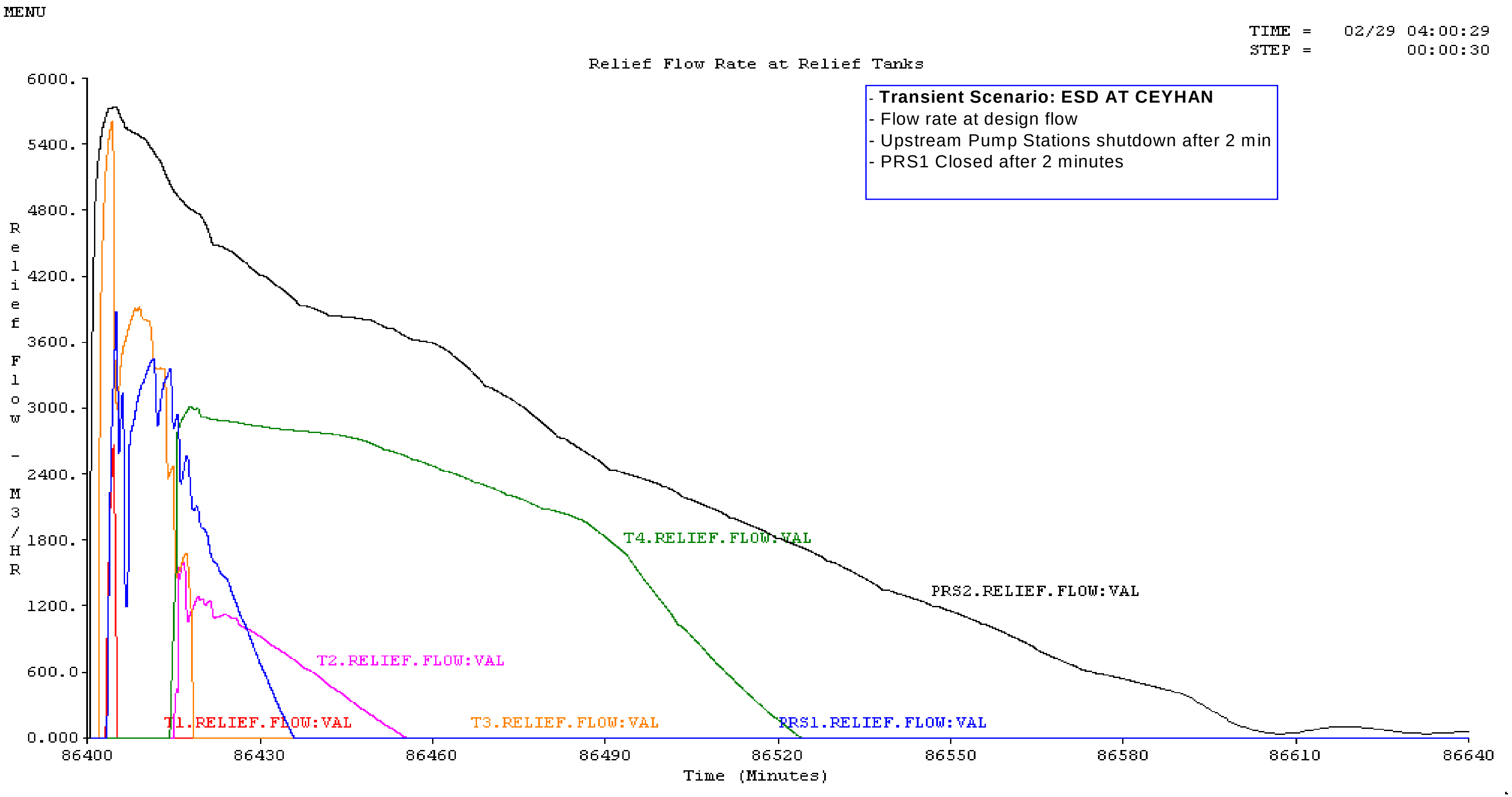

Figure 5.12 Variation in Relief Flow Rate with Time – ESD at Ceyhan Terminal

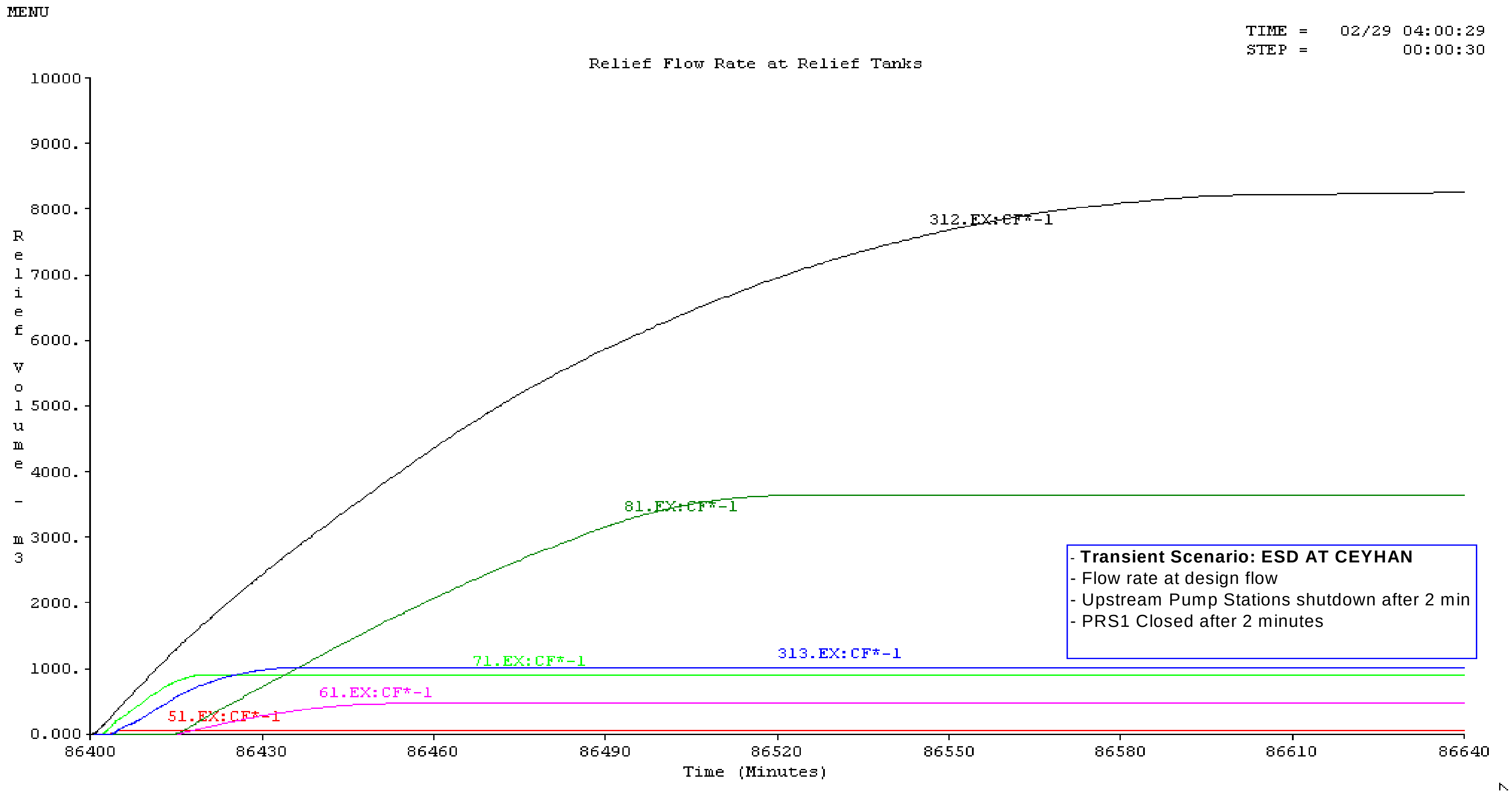

Figure 5.13 Cumulative Relief Volume Variation - ESD at Ceyhan Terminal

The shutdown of the two upstream pump stations will trigger shutdown of two other upstream pump stations until all the pump stations are shutdown. For Turkey section FLOW-PATH monitoring is used to shutdown upstream stations. See Figures 5.1 through 5.13

5.9 Surge due to Block Valve Closure-ICSS Operational

A number of block valves are provided along the pipeline. Unauthorized closure of any of these valves while the pipeline is operating can give rise to transient pressures if the system is not shutdown by ICSS. There are 87 block valves and 14 check valves as noted in Chapter 4. Out of these 4 mainline valves located between pump stations PS-A1 and PS-T1 were selected for transient analysis. These valves are located near the end of each section between two consecutive pump stations. These locations are likely to produce maximum transient pressures. The objective of the analysis is to establish the impact of changes on the transient pressures.

The pipeline was assumed to operate at the design (6700 m^3/h) flow rate. The selected block valve is accidentally closed while the system is in operation. The valve was assumed to close completely in 7 minutes.

If the ICSS is operational, preventive actions may be taken soon after the detection of the start of closure of any mainline block valve. The time interval between detection of start of valve closure and start of the upstream system shutdown was selected to be 2 minutes.

The sequence of events for each block valve was as follows:

- The pipeline is initially operating at design flow rate of 6700 m^3/h in steady state.
- A block valve starts to close at time zero.
- After 2 minutes all of the pump stations are shutdown and the intermediate pressure reducing station block valves are shutdown

5.9.1 Valve AB08 at km 227.427

The variations in pressure along the pipeline after 15 and 30 minutes from the start of valve closure are shown in Figure 5.14. It shows that the maximum transient pressure remains below MAOP.

5.9.2 Valve AB21 at km 435.653

The variations in pressure along the pipeline after 15 and 30 minutes from the start of valve closure are shown in Figures 5.15. It shows that the maximum transient pressure remains below MAOP.

5.9.3 Valve GB05 at km 495.511

The variations in maximum transient pressure and final pressure along the first 550km of pipeline after 30 minutes from the start of valve closure are shown in Figure 5.16. It shows that the maximum transient pressure remains below MAOP.

5.9.4 Valve BVS003 at km 711.875

Figure 5.17 shows the variation in transient pressure in the section of pipe between km 694 and 712 at 10, 15, 30 and 60 minutes after the start of BVS03 valve closure. The system is shutdown in 2 minutes after the start of valve closure. Figure 5.17 shows that the transient pressures are less than MAOP of the pipe.

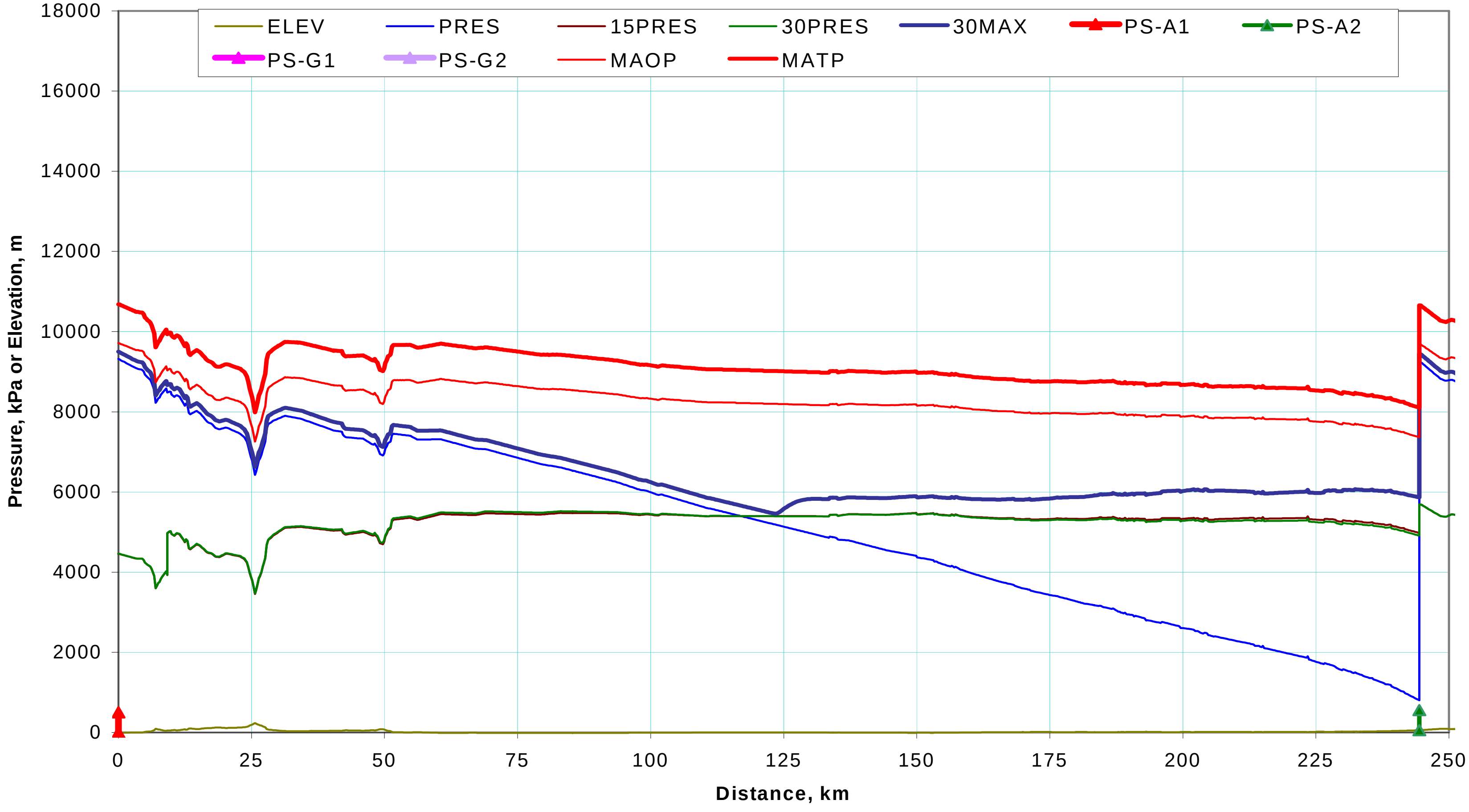

Figure 5.14 Valve AB08 Closes –Pressure Variation km 0 to 250

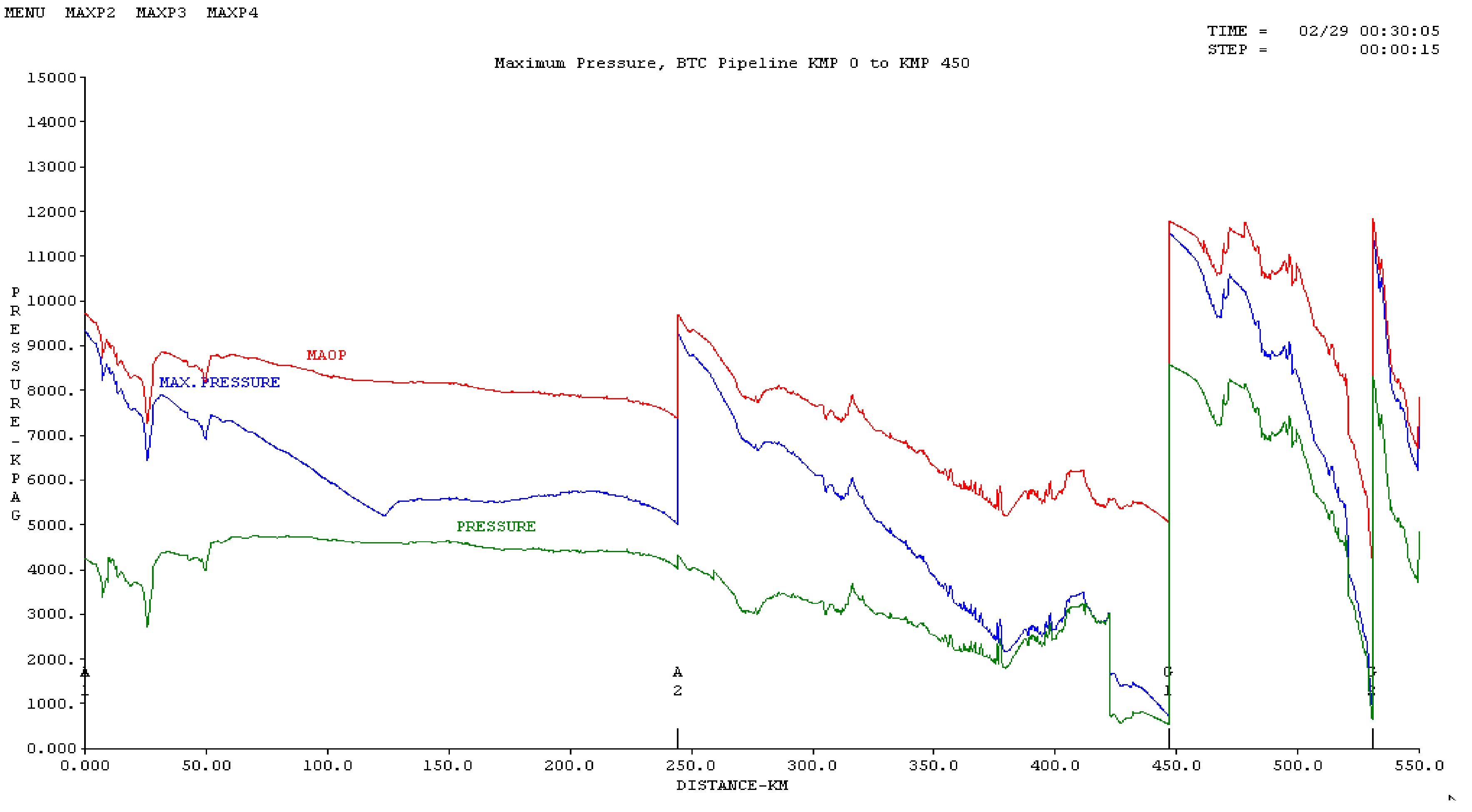

Figure 5.15 Valve AB21 Closes – Max and Current Pressure Variation km 0 to 550

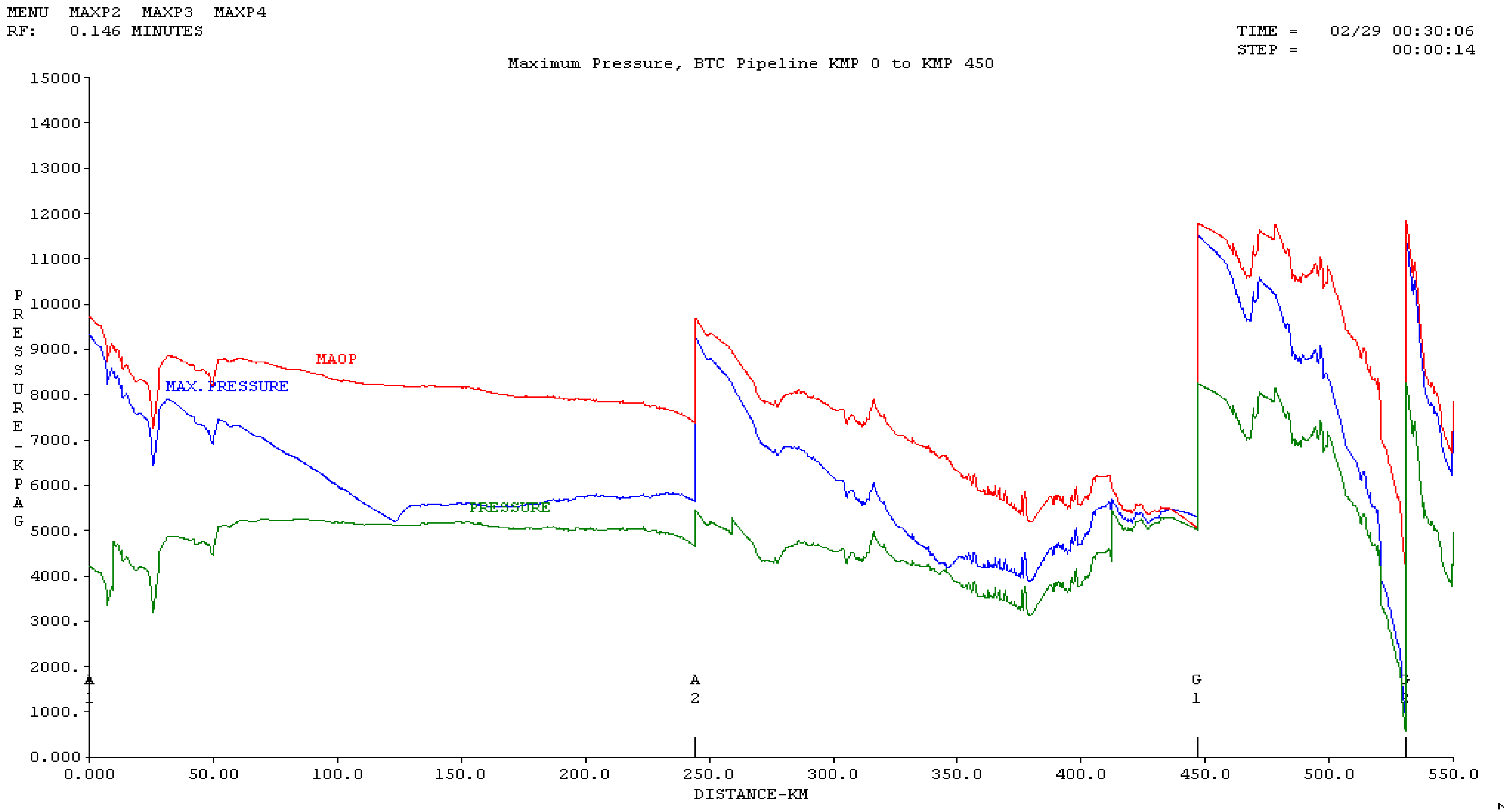

Figure 5.16 Max Transient Pressure Variation Between km 0 to 550 – Valve GB05 Closes and System Shutdown Realizes in 2 Minutes

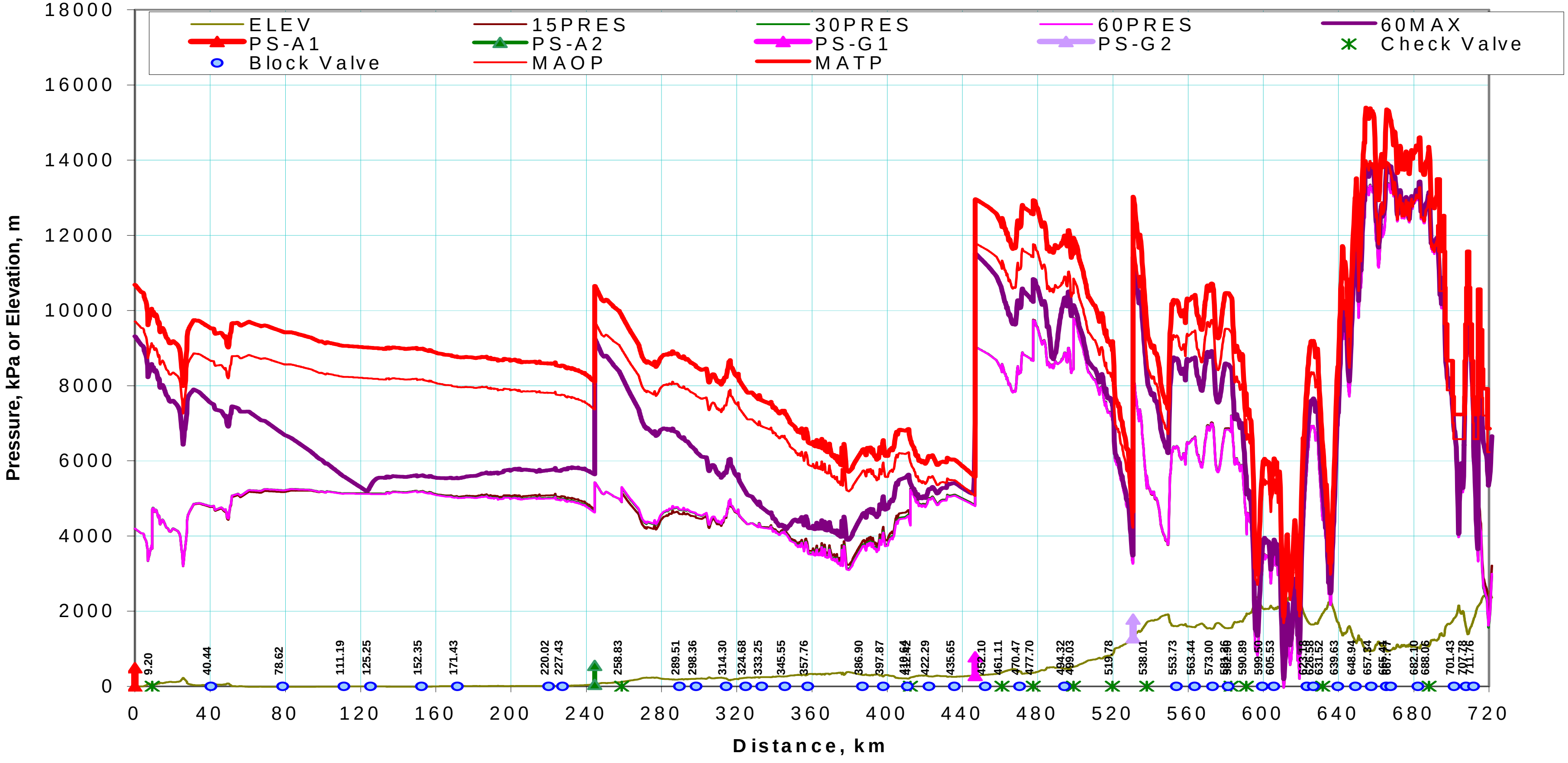

Figure 5.17 BVT 03 Closes – Pressure Variation km 0 to 720

5.9.5 Block Valves Downstream of PS-T1

The transient pressures exceed the maximum allowable transient pressure in certain sections of the pipeline when the following block valves in the Turkey section are accidentally closed while the pipeline is operating at the design throughput:

Valve BVS039 (MLV027) located at KP1406.125 between PS-T3 and PS-T4
Valve BVS051 (MLV033) located at KP1722.257 between IPT1 and TT1
Valve BVS052 (MLV034) located at KP1753.814 between IPT1 and TT1

5.10 Maximum Transient Pressure due to Block Valve Closure

The purpose of this analysis is to summarize the maximum transient pressures resulting from block valve closures when no action is taken by ICSS to reduce the pipeline flow rate and discharge pressure set points to safe values or shutdown of upstream sections of the pipeline. The transient pressures are compared with the maximum allowable pressures corresponding to 80, 90 and 100% of SMYS as well as MAOP and MATP of the pipeline.

The pipeline is assumed to be operating at the design flow rate. The block valve is assumed to close while the pipeline continues to operate until the pump stations are tripped on high discharge pressures. In order to meet the design basis of the pipeline, the maximum transient pressure should not exceed the MATP of the pipeline while the steady pressure after 60 minutes following the start of closure of the block valve should not exceed the MAOP of the pipeline. Only selected valves have been analysed.

5.10.1 Closure of Valve AB08 at km 227.427

The pressure variations along the first 720 km section of pipe at 5, 10, 15, 30, 45 and 60 minutes after the closure of the valve are shown in Figure 5.18.

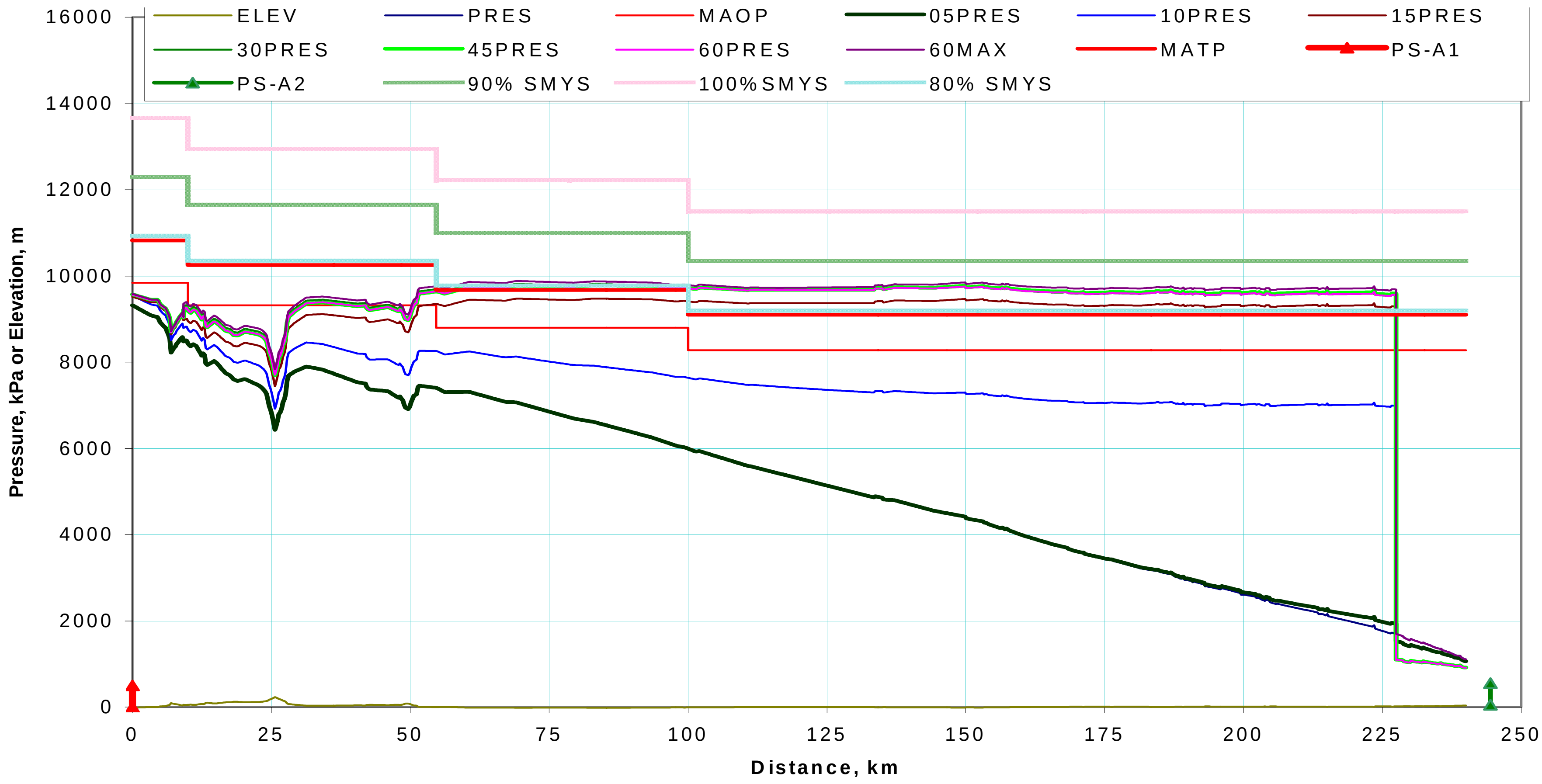

Figure 5.18 Valve ABB08 Closes – Pipeline Continues to Operate Pressure variation Along Pipeline

It shows that the pressure exceeds MAOP in the pipe section upstream of the valve. The maximum pressures were found to be less than pressure corresponding to 90% of SMYS.

5.10.2 Closure of Valve AB21 at km 435.653

The pressure variations along the first 720 km section of pipe at 5, 10, 15, 30, 45 and 60 minutes after the closure of the valve are shown in Figure 5.19.

It shows that the pressure exceeds MAOP in the pipe sections upstream of the valve. The maximum pressures were found to be less than pressure corresponding to 90% of SMYS.

5.10.3 Closure of Valve GB05 at km 495.511

The pressure variations along the first 720 km section of pipe at 5, 10, 15, 30, 45 and 60 minutes after the closure of the valve are shown in Figure 5.20. It shows that the pressure do not exceed MAOP anywhere in the pipe.

5.10.4 Closure of Valve BVS003 at km 711.875

The pressure variations along the first 720 km section of pipe at 5, 10, 15, 30, 45 and 60 minutes after the closure of the valve are shown in Figure 5.21. It shows that the pressure exceeds MAOP in the pipe sections upstream of the valve. Figure 5.22 shows the pipe area upstream of the valve BVS003 at a larger scale to get a better picture of the over pressure condition in the pipe. The maximum pressures were found to be less than pressure corresponding to 100% of SMYS.

5.10.5 Conclusions

Closure of a mainline block valve with no action taken by ICSS gives rise to pressures that exceed MATP for some of the valves.

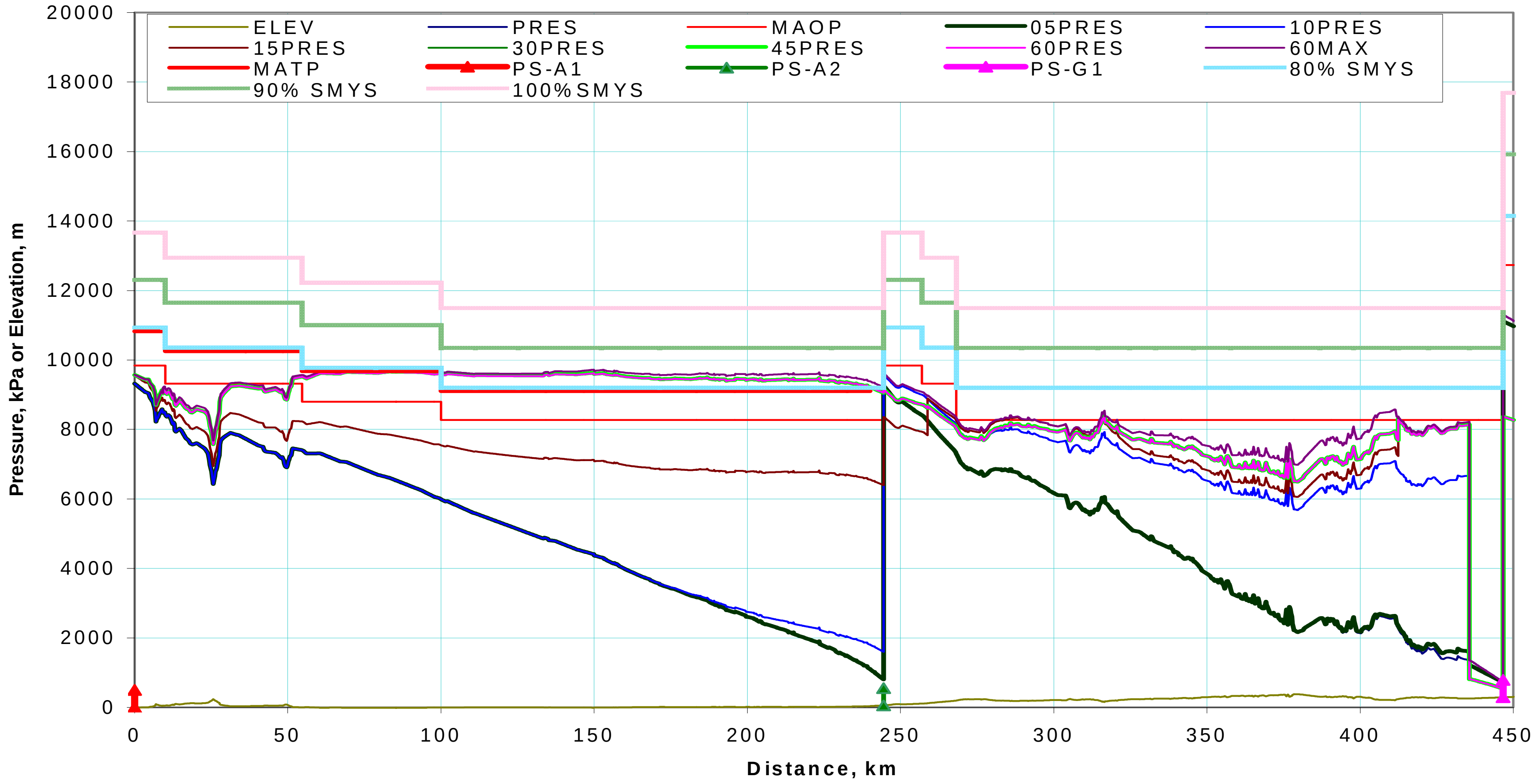

Figure 5.19 Valve ABB22 Closes – Pipeline Continues to Operate Pressure variation Along Pipeline

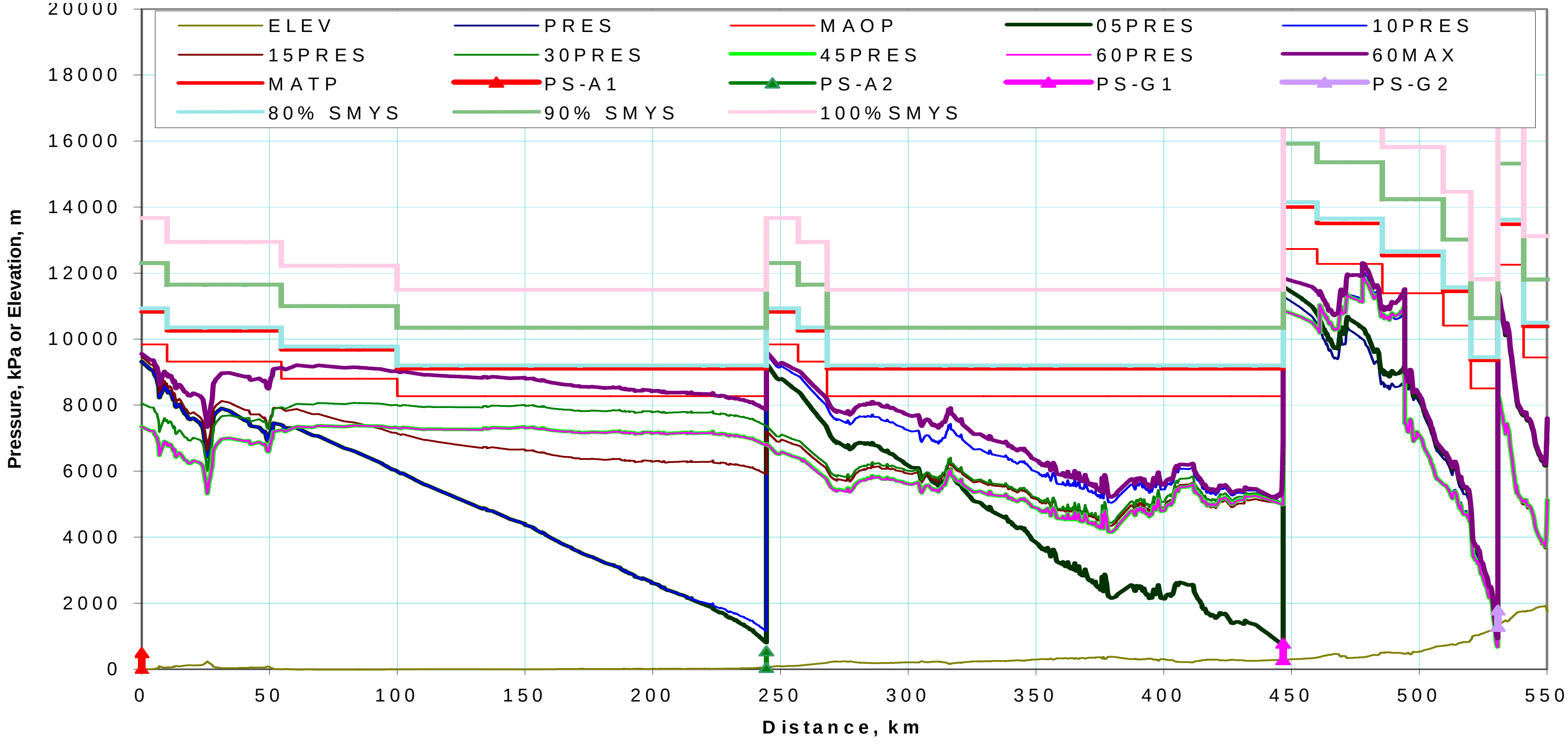

Figure 5.20 Valve GB05 Closes – Pipeline Continues to Operate Pressure variation Along Pipeline

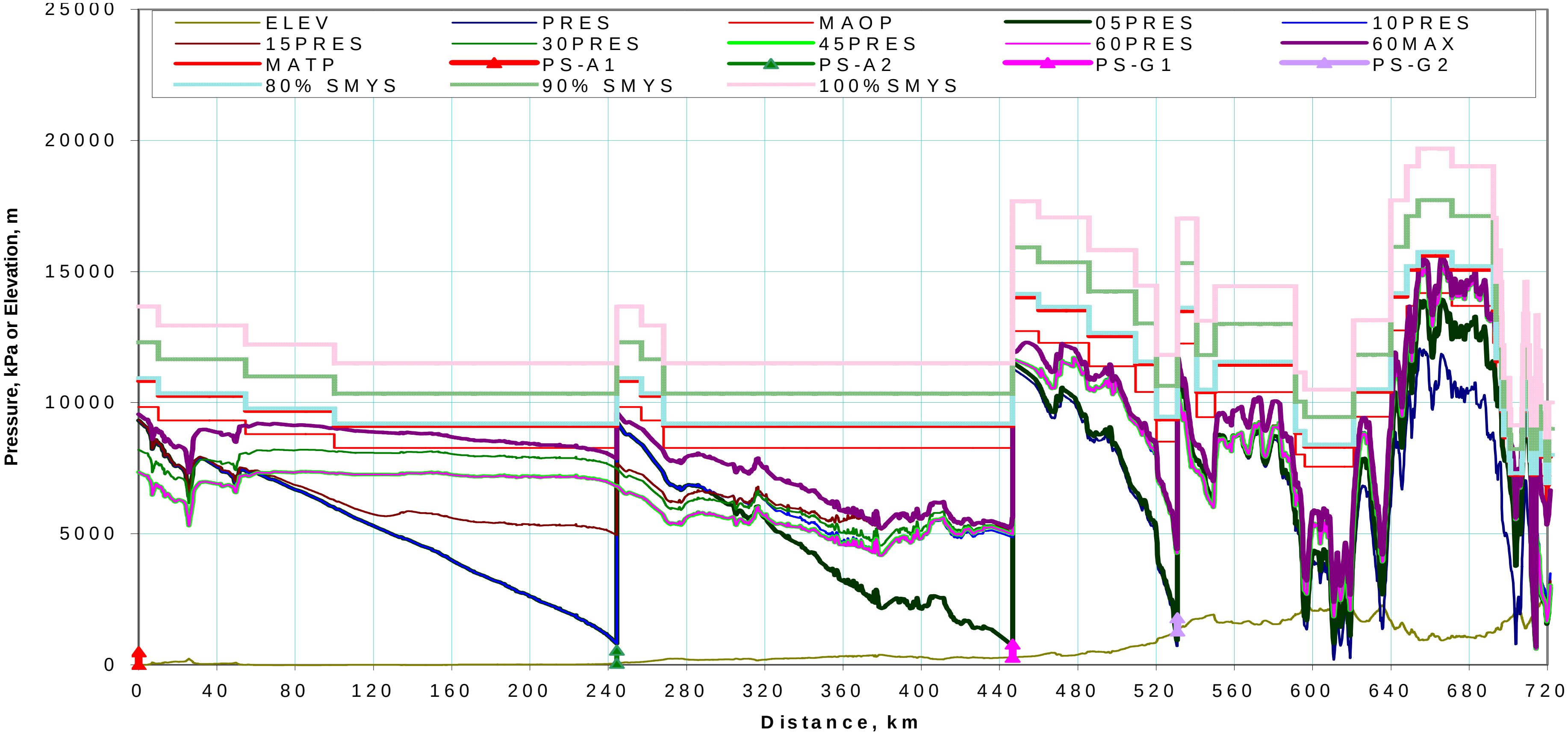

Figure 5.21 BVT 03 Closes – Pipeline Continues to Operate Pressure variation Along Pipeline

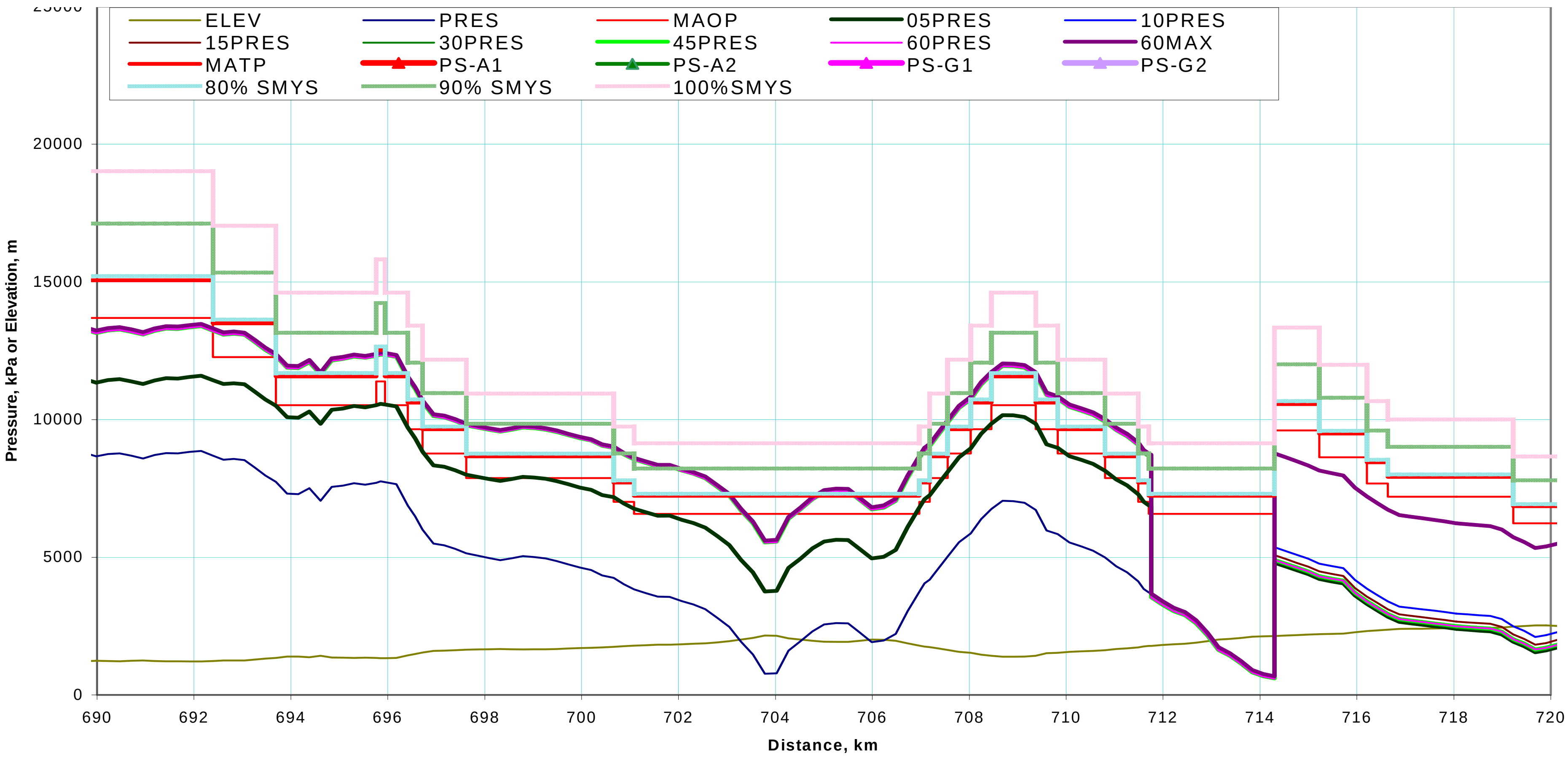

Figure 5.22 BVT 03 Closes – Pipeline Continues to Operate Pressure variation Along Pipeline

The maximum transient pressures were found to be below pressures that give rise to pipe hoop stress equal to SMYS for the valves that have been examined.

5.11 Simulation of Rupture

Simulation of rupture in the pipeline was carried out. Three locations were selected in the Az/Ge section of the pipeline near km 639, 648 and km 665. Seven locations were selected in the Turkey section of the pipeline. The objective of the simulation is to determine if the transient pressures created by closure of mainline block valves against very high flow rates are within acceptable limits or not. The response to rupture will be by the pipeline operators. No automatic ICSS actions are anticipated.

Please note that the location and type of some of the valves have changed since the time when the rupture analysis was carried out. This analysis has not been repeated using the current model. The location and type of valves referred in this section do not match with the current Stoner model data file.

5.11.1 Method of Simulation

A rupture was simulated by attaching a short length of branch pipe with a 42-inch diameter quick opening valve at the location of the rupture. The pipeline is initially operating at design flow rate in steady state condition. At the start of simulation, the 42-inch quick opening (5 sec opening time) valve on the branch is opened. It is assumed that the rupture is confirmed within 10 minutes. The pump stations are shutdown by the operator at 11 minutes after the start of rupture. The mainline block valves on two sides of the rupture are closed by the pipeline operator. These are assumed to start to close at 11 minutes after rupture occurs.

5.11.2 Simulation Results-Rupture at 639.854

The variation in flow rate and cumulative flow from the rupture are shown in Figure 5.23. It shows that immediately after the rupture, the flow rate peaks at about 63000m^3/h and then it starts to decrease with time. The flow from the rupture continues at more than 6700 m^3/h for the first 15 minutes after rupture. The flow stops after 19 minutes since the mainline block valve GB21 located at km 639.591 closes completely at 18 minutes. The simulation was carried out for 30 minutes. The total amount of oil released in 30 minutes was estimated to be 5075 cubic metres.

The variation of flow rate and pressure drop for the first 3 minutes at the rupture (across the 42-inch valve used to simulate rupture) are shown in Figure 5.24. It shows that the maximum flow of 63000m3/h occurs after about 0.4 second. The pressure drop across the rupture was estimated to be 4 kPag.

The downstream pump station (PS-T1) trips soon after the rupture due to reduction in suction pressure as shown in Figure 5.25. The impact of rupture on the upstream pump station is not significant as shown in Figure 5.26. It shows that the flow rate, suction pressure as well as discharge pressure remain about constant until the station is tripped at 11 minutes after the start of rupture.

The nearest check valve upstream of the rupture is GC19 located at km 631.524. Figure 5.27 shows variation in pressure and flow at check valve GC19. It shows that the check valve remains open until the mainline block valves are completely closed 18 minutes after the start of rupture. The maximum flow rate of about 13700m^3/h through the check valve GC19 occurs at about one minute after the rupture.

The nearest check valve downstream of rupture is GC23 located at km 667.771. Figure 5.28 shows variation in pressure and flow at check valve GC23. It shows that the check valve closes about 0.5 minute after the start of rupture. Large variations in pressure upstream of the check valve are caused by the variation in flow rate between rupture point and the check valve.

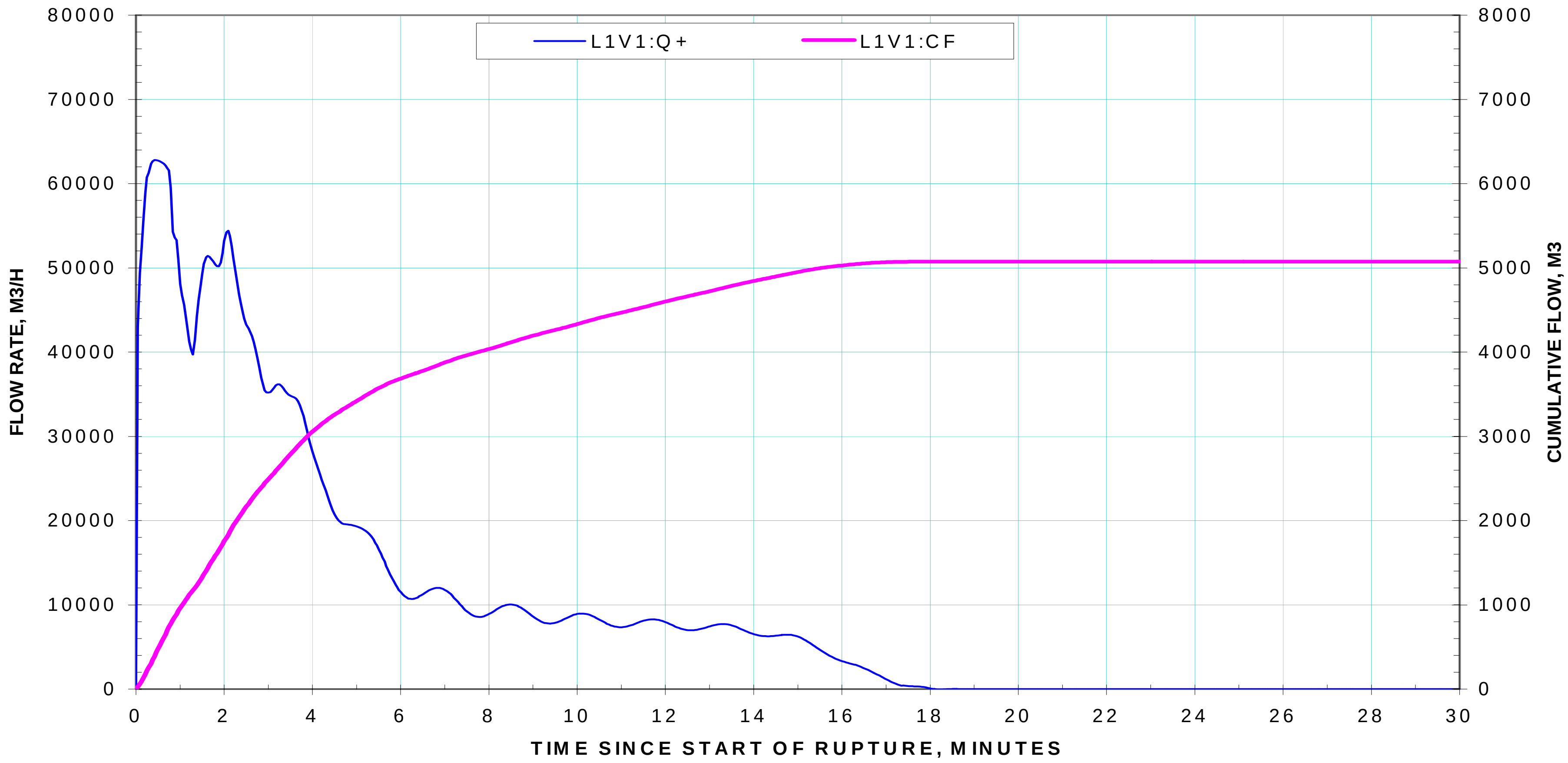

Figure 5.23 Rupture Flow at km 639, 10 minutes after Shutdown of the Sytem

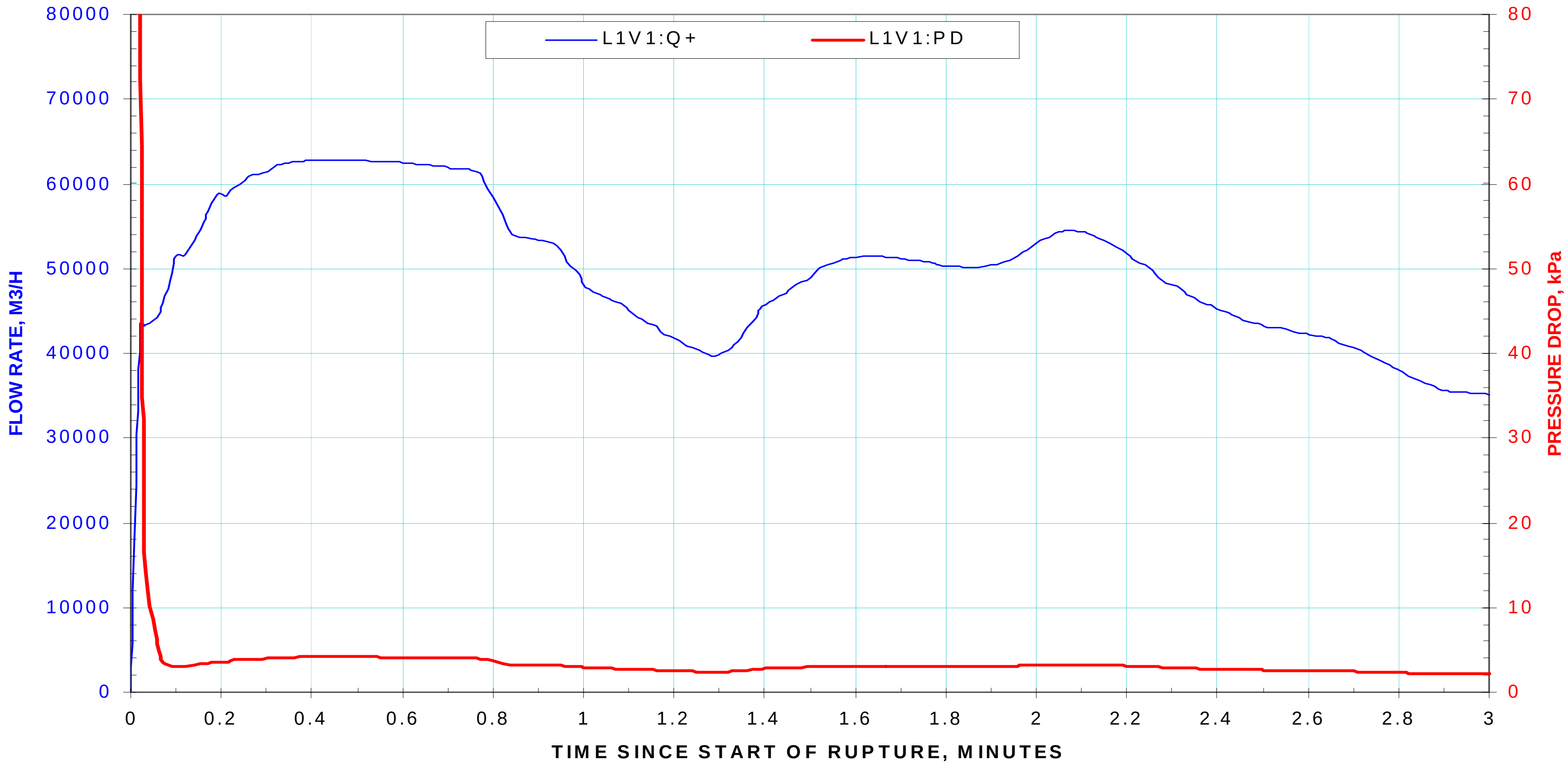

Figure 5.24 Rupture Flow at km 639, 10 minutes after Shutdown of the Sytem

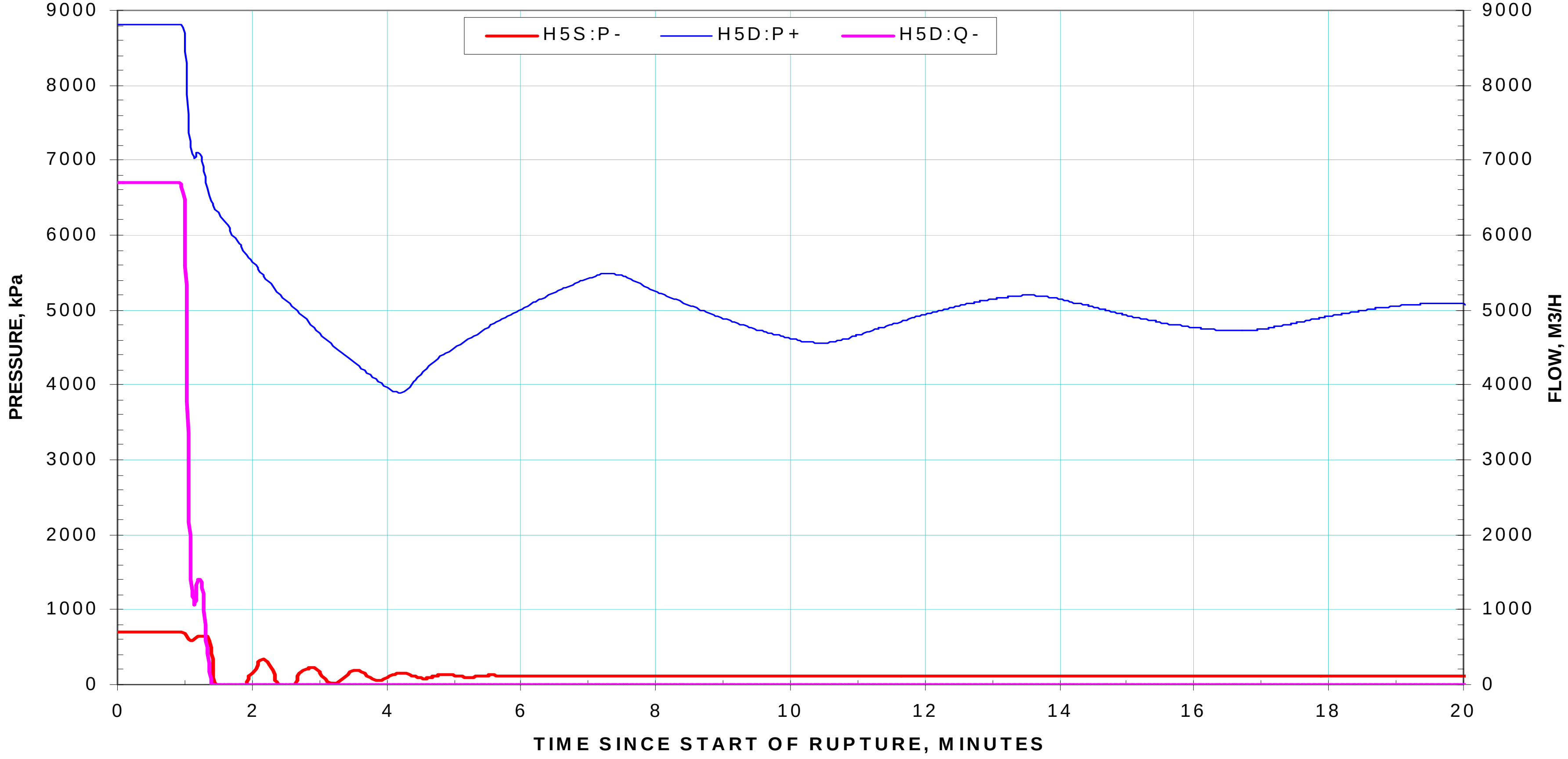

Figure 5.25 Rupture Flow at km 639.PS-T1 station 10 minutes after Shutdown of the Sytem

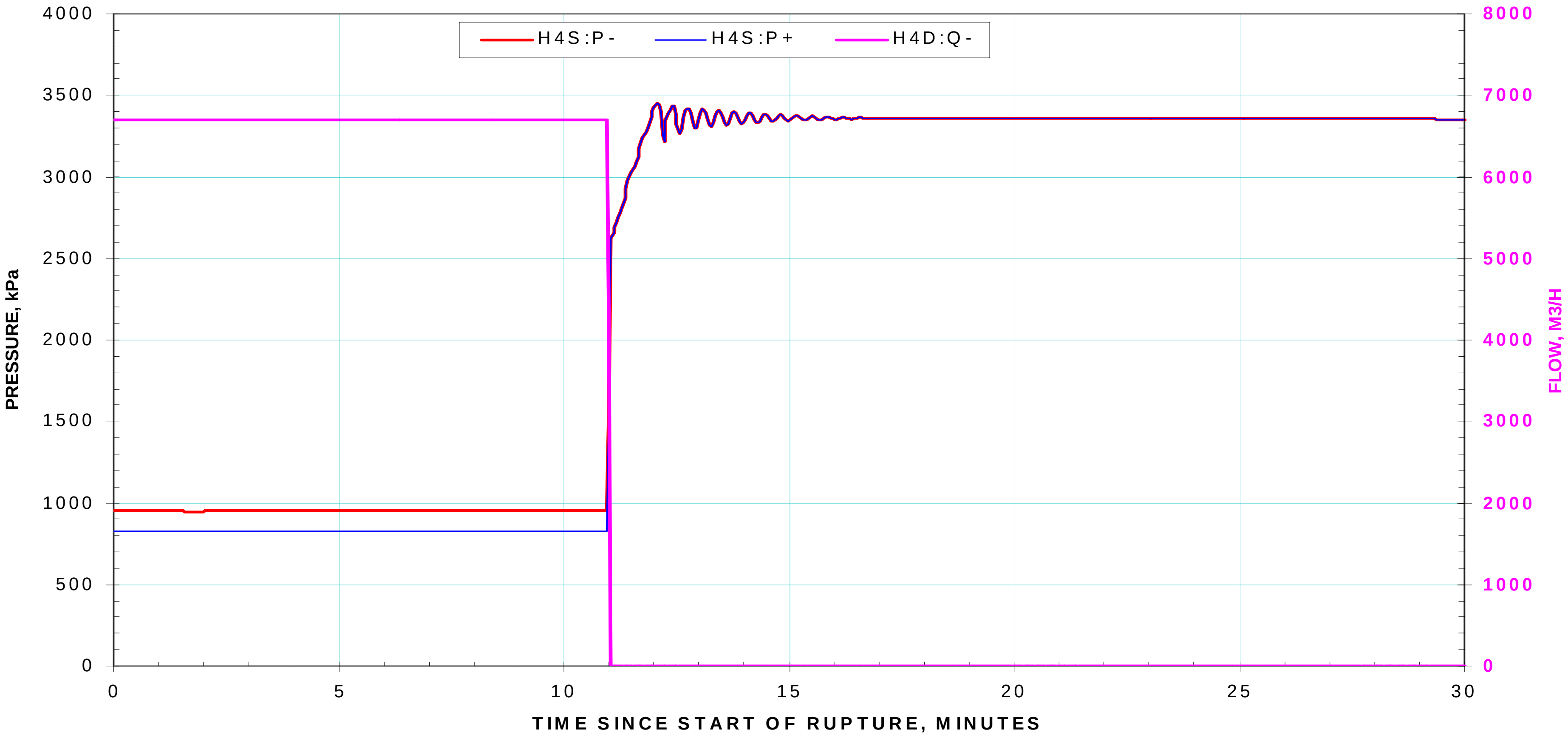

Figure 5.26 Rupture Flow at km 639.PS-G2 station 10 minutes after Shutdown of the Sytem

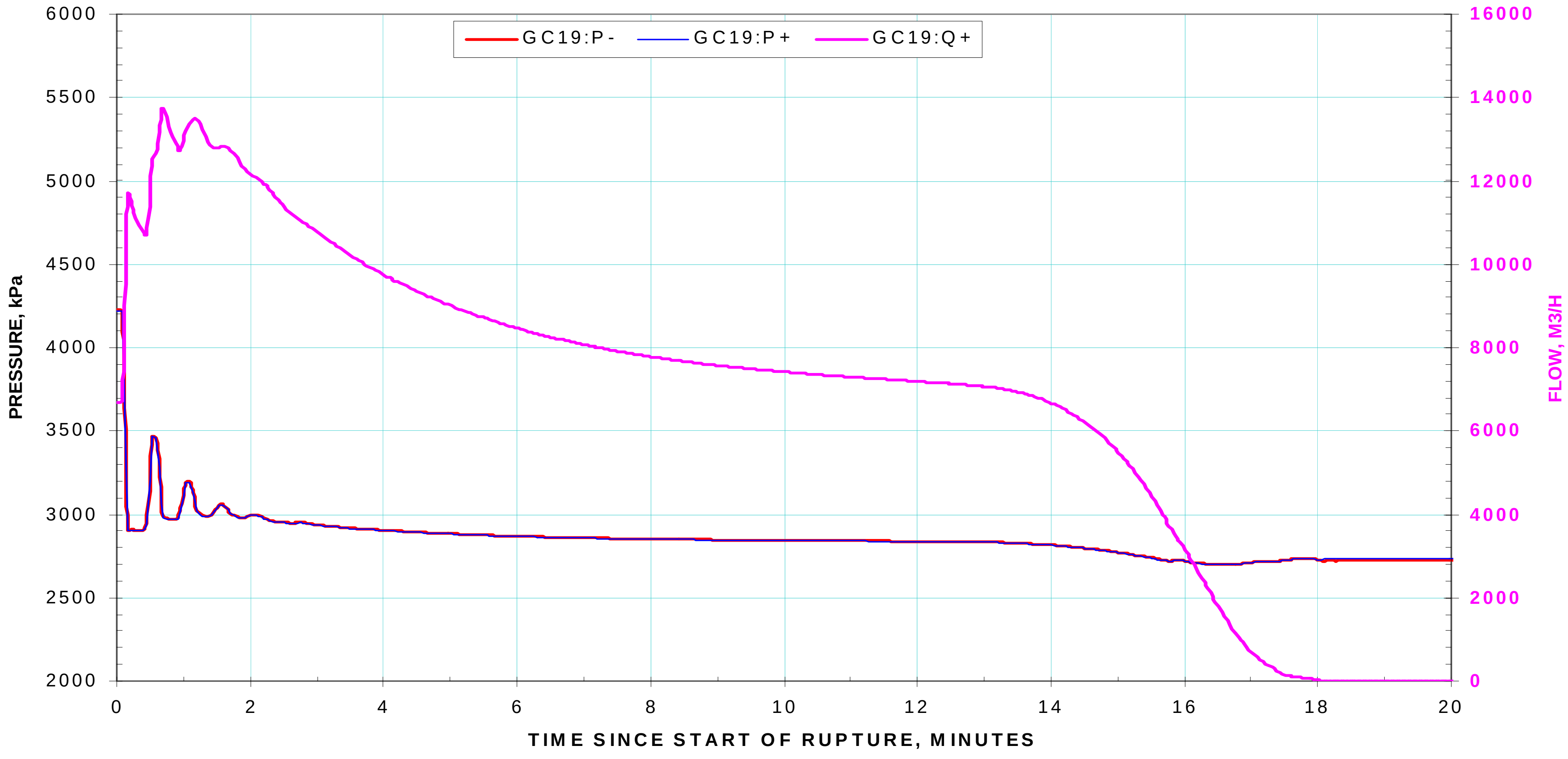

Figure 5.27 Rupture Flow at km 639.Check Valve GC19 10 minutes after Shutdown of the Sytem

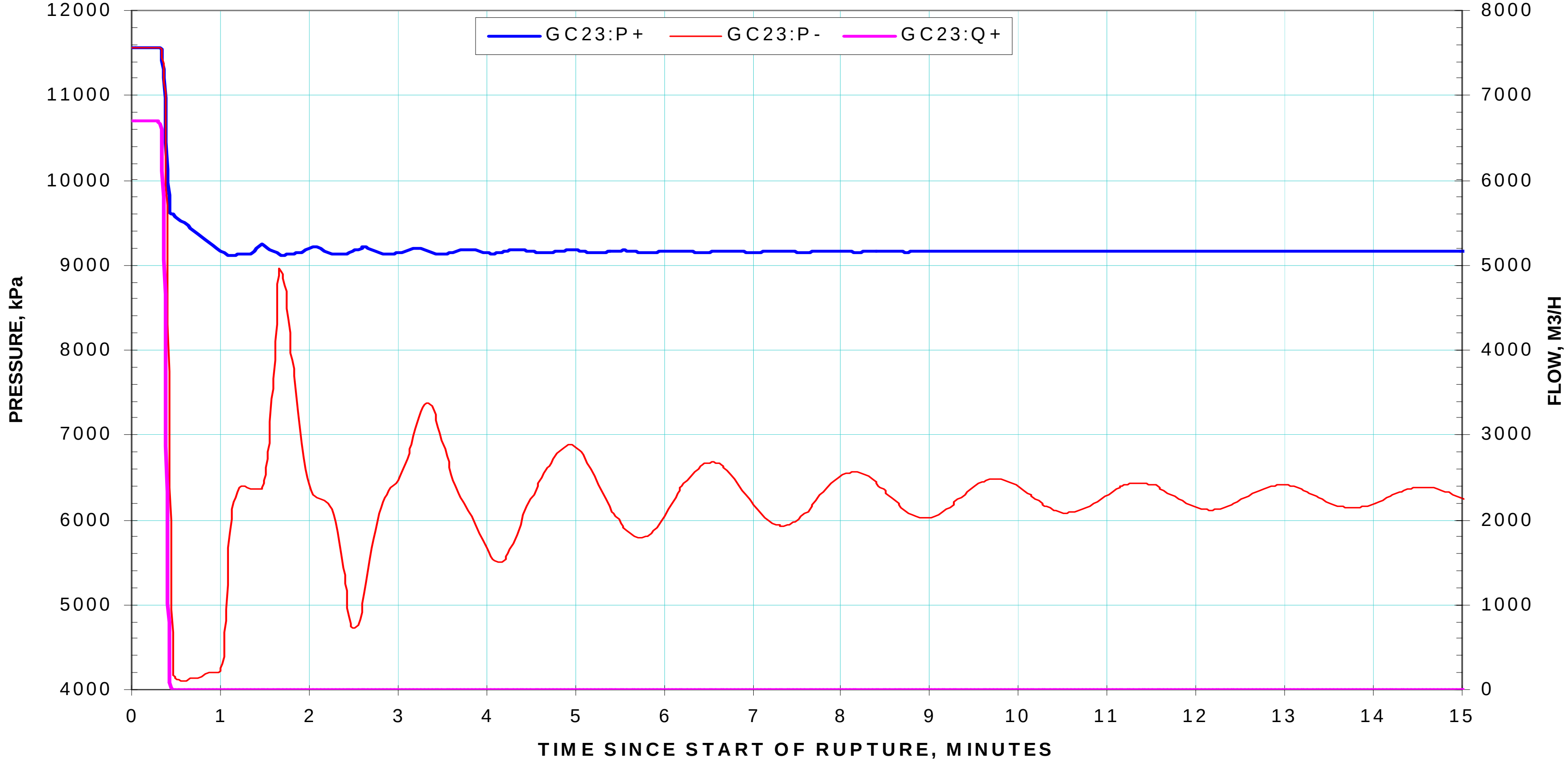

Figure 5.28 Rupture Flow at km 639.Check Valve GC23 10 minutes after Shutdown of the Sytem

5.11.3 Operating Pump Trip at PS-T1

This case assumes that the pipeline is initially operating in steady state at the design flow rate of 6700 m^3/h. The upstream stations are shutdown 15 minutes after the pump trip at PS-T1 while the downstream stations shutdown on low suction pressure.

5.11.4 Shutdown Sequence

The sequence of events for this case is summarized in Table 5.9.

Table 5.9: Shutdown Sequence

Time, minutes	Action
0	Stop Pumps 5P01, 5P02, 5P03, 5P04 Increase the PS-A1 through PS-G2 discharge controller and discharge pressure trip set points to high values given in Table 5.5
15.0	Stop Pumps 4P01, 4P02, 4P03, 4P04 Stop Pumps 3P01, 3P02, 3P03, 3P04 Stop Pumps 2P01, 2P02 and 2P03 at PS-A2 Stop Pumps 1P01, 1P02, 1P03 and 1P04 at PS-A1
Various	PS-4, 5, 6, 7 and 8 pumps trip on low suction pressure

5.11.5 Simulation Results

The pipeline profile and head and flow variation when PS-G1, PS-A2 and PS-A1 trip following PS-T1 shutdown are shown in Figures 5.29 through 5.31.

The maximum pressure envelope along the first 450 km of the pipeline is shown in Figure 5.32. This figure shows that the maximum transient pressure exceeds MAOP between km 54 and km 170. The maximum over pressure occurs near KM100.

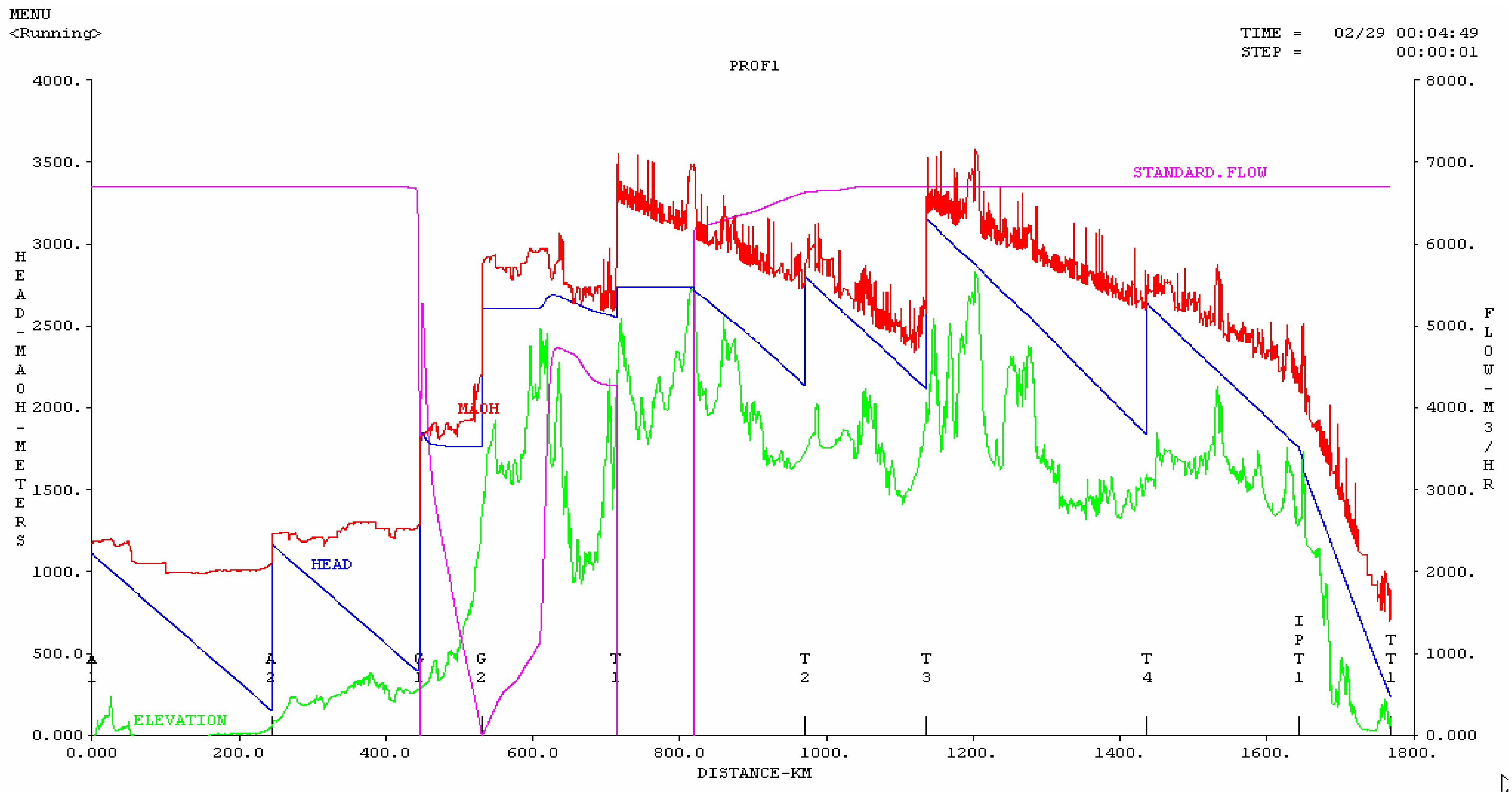

Figure 5.29 Pressure Variation Following PS-A2 and PS-G1 Trips

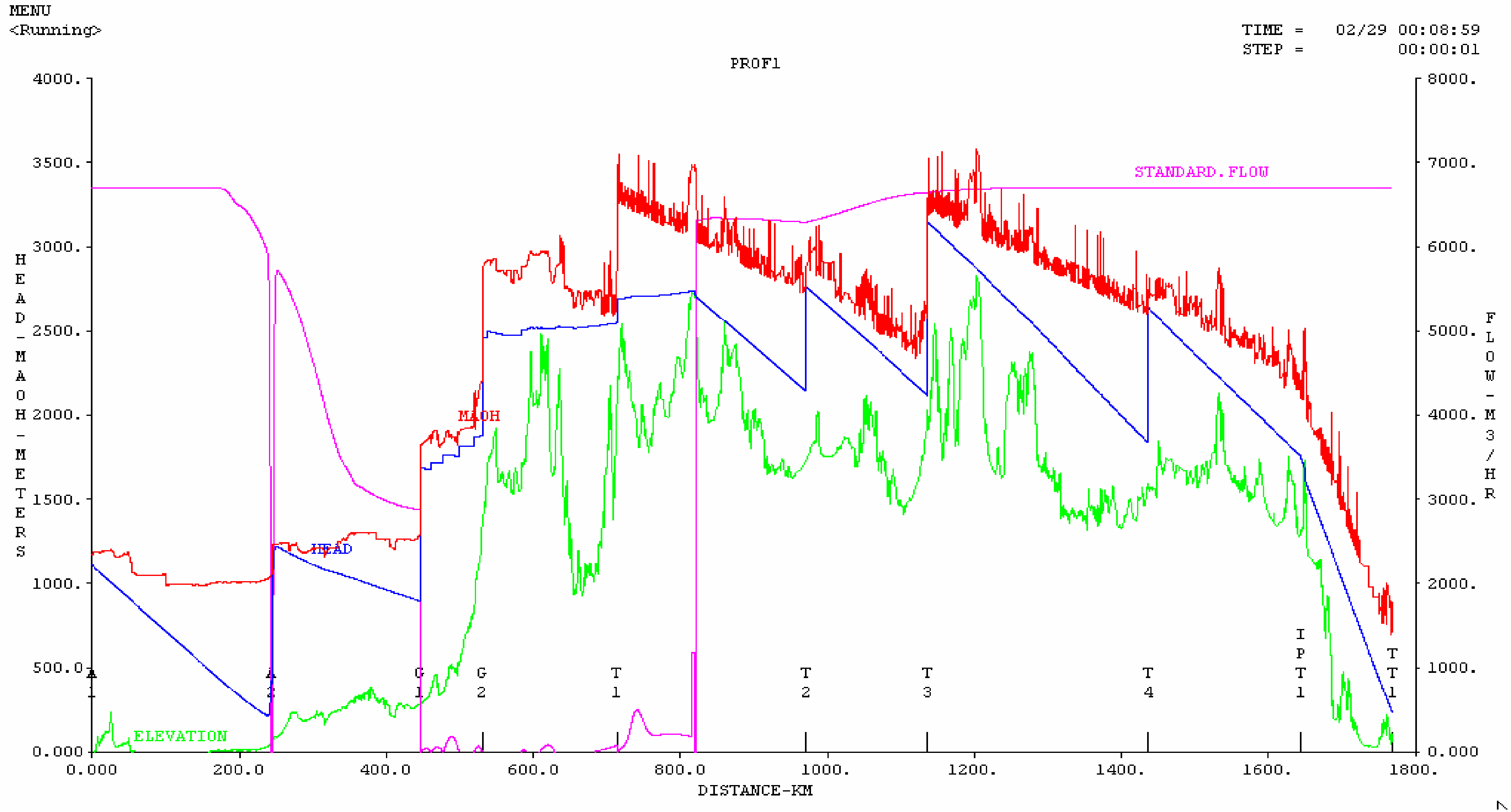

Figure 5.30 Pressure Variation Following PS-T1 and PS-A2 Trips

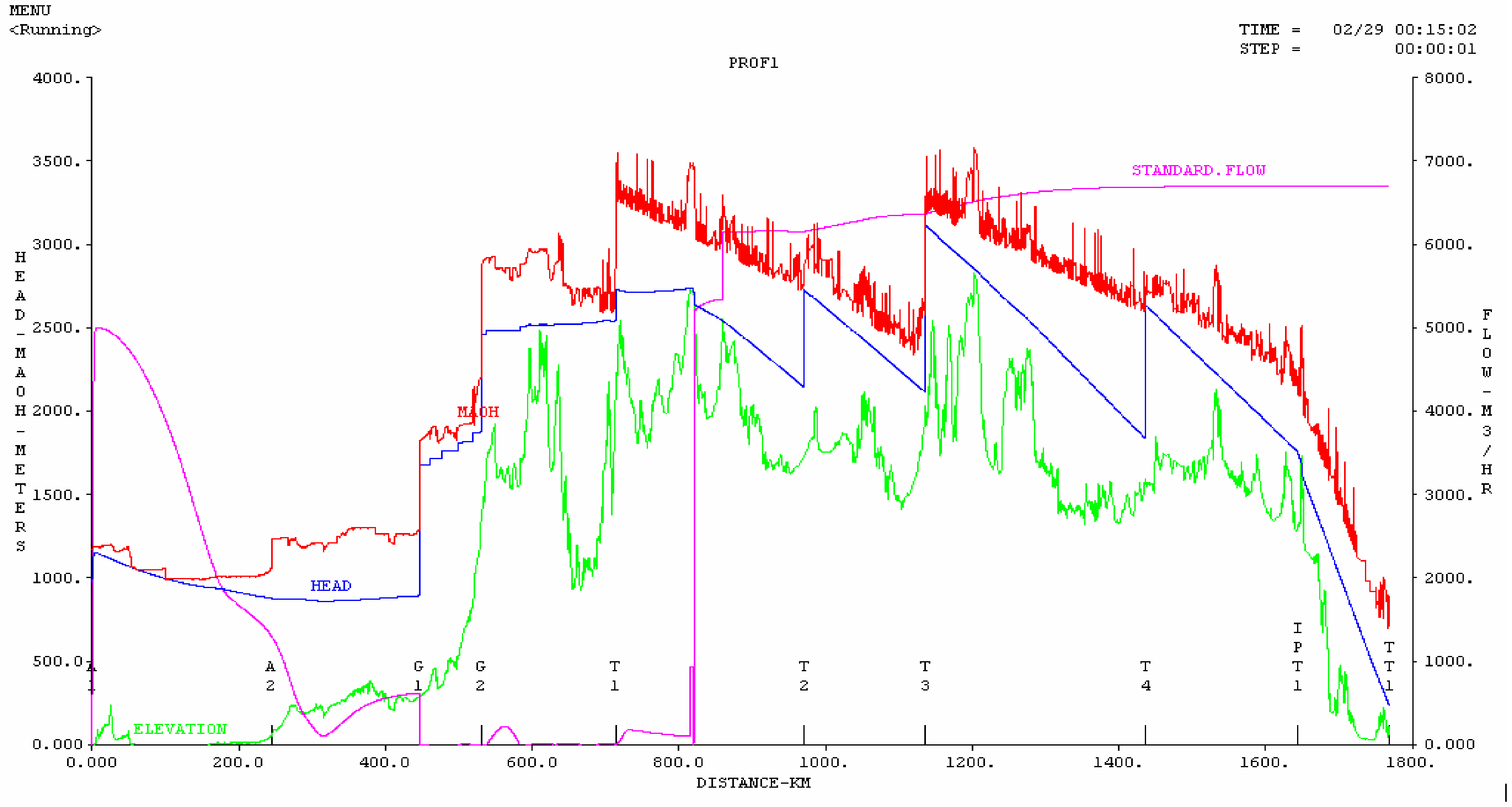

Figure 5.31 Pressure Variation Following PS-T1 and PS-A1 Trips

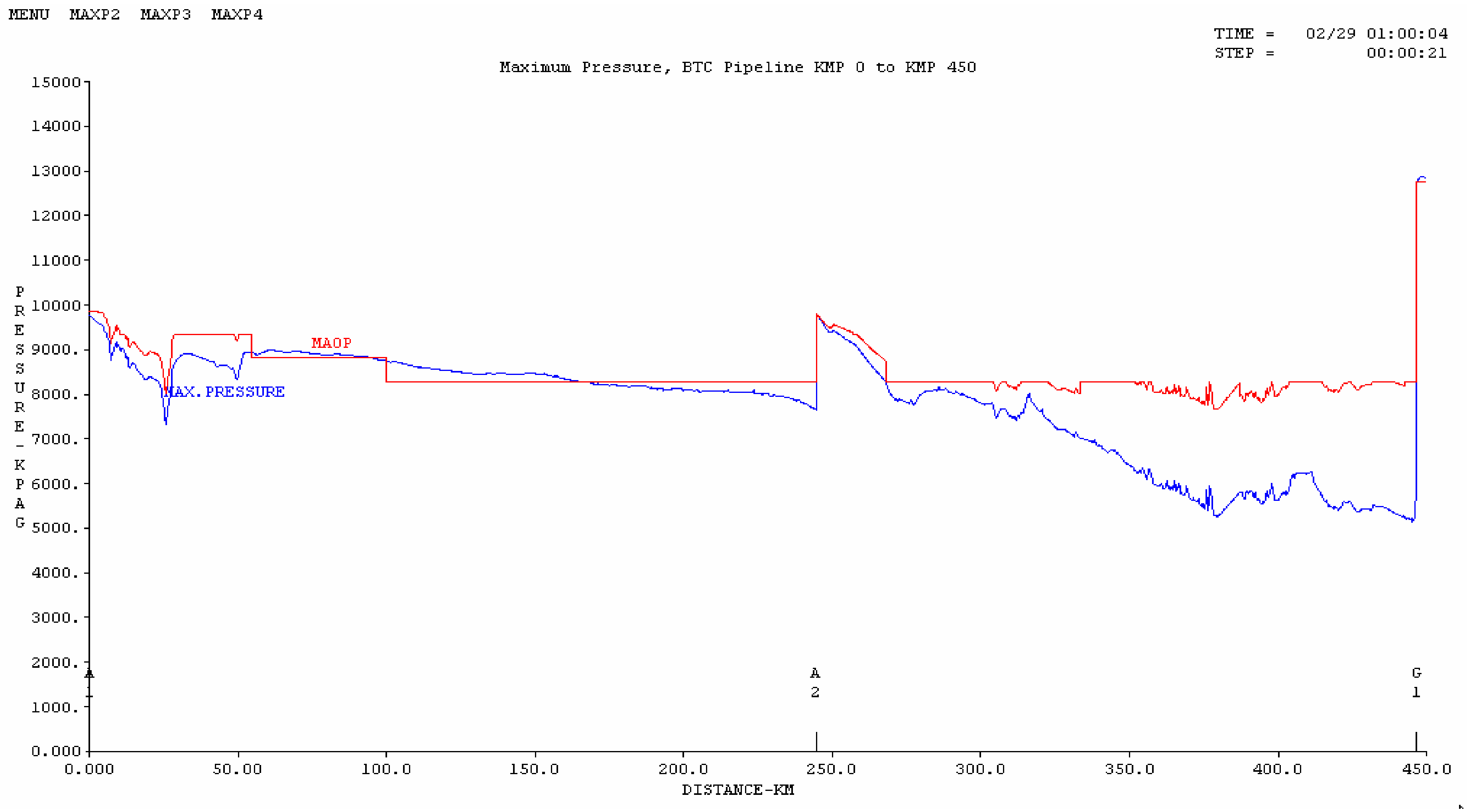

Figure 5.32 Pressure Variation Following PS-T1 Trips

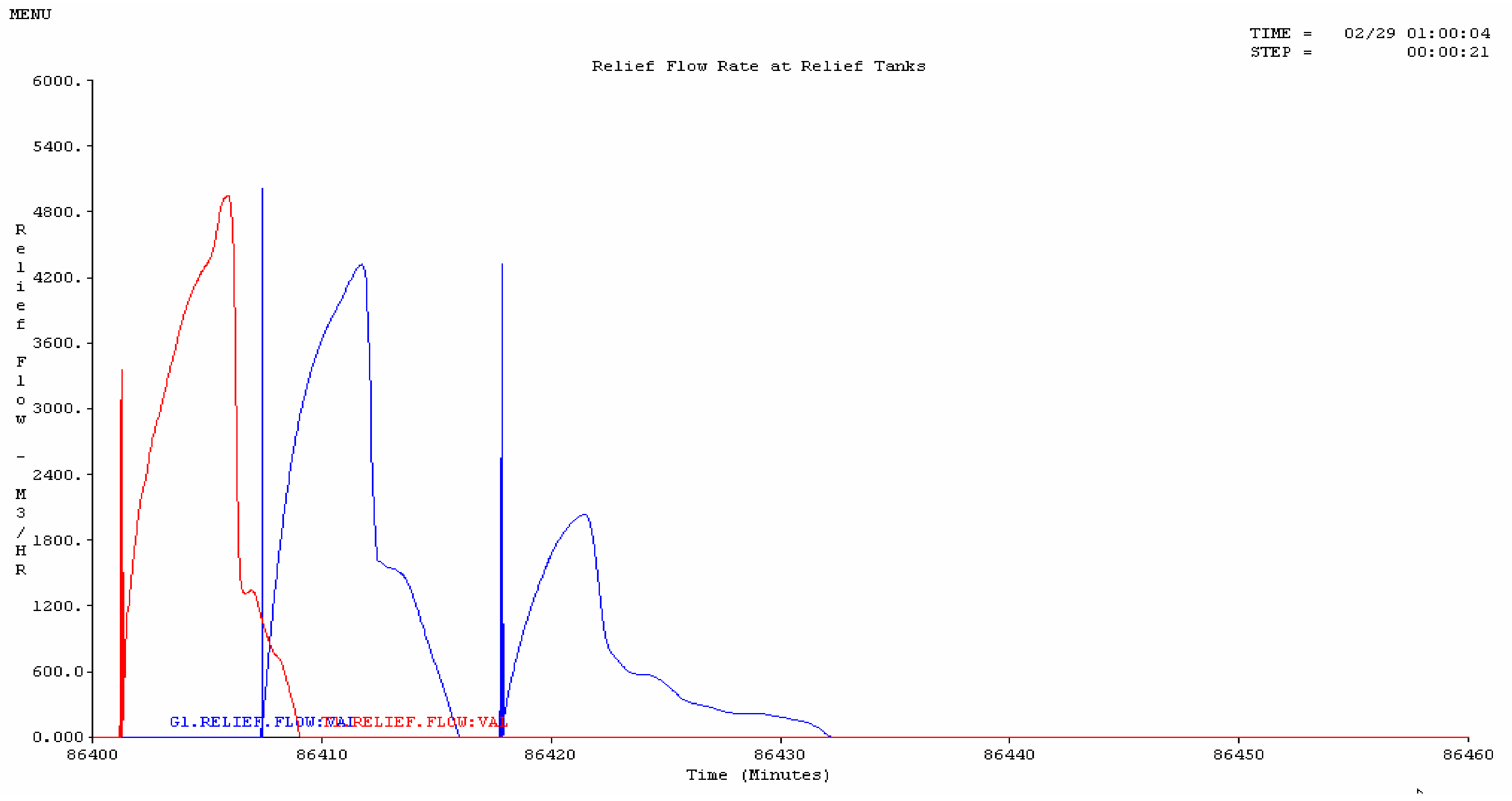

Figure 5.33 Relief Systems Following PS-T1 Trips

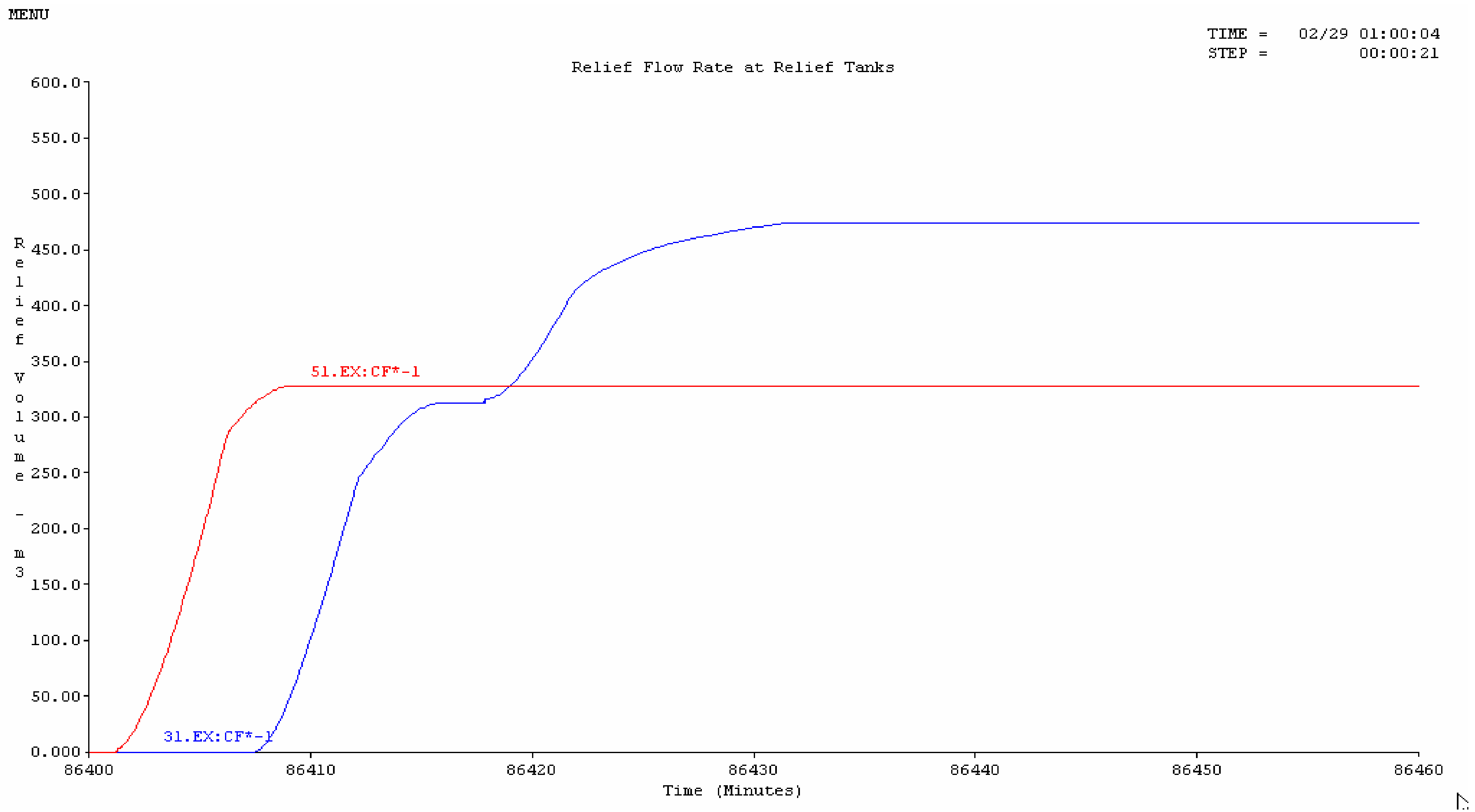

Figure 5.34 Cumulative Volume of Relief Systems Following PS-T1 Trips

The relief system at PS-G1 and PS-T1 are activated during shutdown of the system. The variation in flow rate and cumulative flow with time are shown in Figures 5.33 and 5.34 respectively. These figures show that the flow through the relief systems stops in about 32 minutes.

The total amount of crude oil released through the relief systems at PS-G1 was estimated to be about 475 cubic meters. The maximum flow through the relief system was estimated to be 4300 m^3/h.

The total amount of crude oil released through the relief systems at PS-T1 was estimated to be about 330 cubic meters. The maximum flow through the relief system was estimated to be 4900 m^3/h.

5.11.6 Recommended Set Points

The results of simulations have shown that the mainline pump station trip set points for the first four pump stations can be increased all the way to the MAOP of the pipeline just downstream of the pump station. The recommended values of the pump station trip and controller set points are given in Table 5.10

The pump station trip set points have been set about 500 kPag above the estimated operating pressure at design flow rate to allow some tolerance to variations in transmitter calibrations. The discharge pressure controller set points have been selected 200 kPag below the trip set point. It should be recognized that the controller set points should be adjusted to a lower value when operating at safe flow rates. The discharge pressure controller set points are about 300 kPag above the maximum steady state operating pressure at design flow rate. Assuming a pressure range of 0 to 15000 kPag, the margin is 2% of the full scale.

Table 5.10

Recommended Discharge Pressure Controller and Trip Set Points

Pump Station	Set Point Pressure, kPag			
	Discharge Pressure Controller		Discharge Pressure Trip	
	Current Value	Recommended	Current Value	Recommended
PS-A1	9500	9550	9650	9750
PS-A2	9450	9500	9600	9750
PS-G1	11500	11800	11650	12050
PS-G2	11650	11800	11800	12050

5.11.7 Pump Trip Set Point

The mainline pumps are provided with individual pump trip switch in order to protect the pump piping if the pump station trip switches fail to trip the pumps. The pump trip set point should be 500 kPag above the pump station trip set point. The individual pump trip set points are given in Table 5.11

Table 5.11: Recommended Individual Pump Trip Set Points for Az/Ge Pumps

Pump Station	Individual Pump Trip Set Point kPag
PS-A1	10300
PS-A2	10300
PS-G1	12700
PS-G2	12700

5.11.8 Conclusions

The potential for increasing the discharge pressure trip and control set points was examined. Recommended values for these points have been given based on potential MAOP based on hydro-test pressure.

5.12 Block Valve BVS003 Closes in 4 Min-Upstream Station Fail to Trip

This is a special case to investigate the impact of shorter mainline block valve closure time on maximum transient pressure.

The pressures at PS-A1, A2, G1 and G2 increase to their respective controller set points while the flow rates decrease with time until the flow stops at PS-G1 and G2 and drops to a steady state value of about 4100 m^3/h at PS-A1 and A2. The pump station PS-T1 trips on low suction pressure. The relief system at PS-G1 is activated as the suction pressure at that pump station increases following shutdown of pumps due to low flow rate. The maximum overpressure occurs between KM 540 and KM 711.

The maximum transient pressure exceeds MAOP in some of the sections. Maximum overpressure occurs upstream of valve BVS003 near KM 711.875. Note that the discharge pressure increases to the controller set point while the flow rate decreases with time. Relief system at PS-G1 is activated. The relief system keeps the transient pressures below MAOP in the section of pipe upstream of PS-G1. The closure time of mainline block valve does not have any effect on the maximum transient pressure and additional valve cases have not been analysed.

5.12.1 Conclusions

The simulation results indicate that for the Az/Ge section of pipe the maximum transient pressures exceed the MATP but do not give rise to pipe stress greater than SMYS of the pipe steel.

CHAPTER 6

CONCLUSIONS & RECOMMENDED MEASURES

The scenarios and related conclusions & recommendations which can be generated from SPS simulations presented are below in Table 6.1

Table 6.1 Scenarios and Conclusions

	Scenario	**Conclusions/Recommendations**
1	Normal Pipeline Shutdown	Transient pressures remain below MAOP. The pump station shutdowns could be staggered to eliminate relief valve activation in the Turkey section.
2	Emergency pipeline Shut-down	Transient pressures remain below MAOP. Re-lief occurs in all sections.
3	Normal Start up	Transient pressures remain below MAOP. Se-quence must be confirmed during commission-ing.
4	SSD or ESD at a Pump Sta-tion or at Ceyhan – ICSS Active	Transient pressures remain below MAOP. Upstream stations shutdown by ICSS within 2 minutes after ESD/SSD.

Table 6.1 Scenarios and Conclusions-continues		
	Scenario	**Conclusions/Recommendations**
5	ESD at a Pump Station or at IPT1 – ICSS Failure	Transient pressures remain below MAOP. A communications failure to a station triggers ISS at the upstream station to shut it down after 15 minutes. (This is needed to limit amount of relief)
6	SSD at a Pump Station – ICSS Failure	Same as in item 5 above
7	Unauthorized block Valve Closure – ICSS Active	ICSS issues SSD for two immediately upstream pump stations within 2 minutes after detecting start of valve closure. Transient pressures remain below MAOP with recommended action.
8	Unauthorized block Valve Closure – ICSS Failure	For valves upstream of PS-T1 the pipeline flow rate is reduced to safe flow value and the discharge pressure controller set points lowered to corresponding values within 1 minute after ICSS failure to a valve.Transient pressures remain below MAOP.
9	Unauthorized block Valve Closure – ICSS Action overridden.	If the upstream pump stations are not shutdown or the flow is not reduced then the transient pressures may exceed the allowable pressures. The maximum transient pressures were found to develop hoop stress less than SMYS of the pipe steel for valves upstream of PS-T1. Prevent override of ICSS

Table 6.1 Scenarios and Conclusions-continues		
	Scenario	**Conclusions/Recommendations**
10	Pump Station Discharge Header (PAHH) trip command Failure: SSD or ESD at PS-T1	The relief system at PS-T1 is activated. The upstream pump stations should be tripped within 15 minutes after activation of relief valve, otherwise the relief tanks will overflow. The operator has responsibility of shutting down the pipeline within 15 minutes in the event of a station trip that is not initiated by the ICSS. Maximum transient pressures above MATP but below SMYS.
11	Pump Station Discharge Header (PAHH) trip command Failure: SSD or ESD at PS-G1 or G2	The relief system at PS-G1 is activated. The upstream pump stations should be tripped within 15 minutes after activation of relief valve, otherwise the relief tanks at PS-G1 will overflow. The operator has responsibility of shutting down the pipeline within 15 minutes in the event of a station trip that is not initiated by the ICSS.Maximum transient pressures above MATP but below SMYS. .
12	Pump Station trip command Failure Unauthorized closure of selected block valves in Az/Ge section.	Maximum transient pressures above acceptable limits. The pipe hoop stress remains below SMYS. Not a likely scenario. No action from ICSS.

Table 6.1 Scenarios and Conclusions-continues		
	Scenario	**Conclusions/Recommendations**
13	One unit trip at a Pump Station	The next available duty pump is started by PCS if available. Transient pressures remain below MAOP.

Any pipeline system can be simulated by this programme but the system should be defined properly. Besides the transients of the long pipelines like BTC, transients in smaller systems could be simulated also. Since the steady state conditions are the initial conditions required for the transient analysis, it is important to define the steady state parameters .

Transient flow analysis should be used in design, construction and operation of pipelines. In this study, after the pipeline system is defined properly, different scenarios are applied to the system and the design is checked for the transient flow conditions. If there exists a problem during unsteady flow conditions, it will be economical to make the changes on the pipeline system before the actual construction begins.

Now that all the scenarios are investigated it can be stated with a great confidence at the beginning of the commissioning phase of the BTC pipeline, it constitutes an optimised and safe pipeline system with minimized residual risks in regard to hydraulics due to detailed state of the art investigations. In the course of detailed investigations concerning steady flow and transient analysis engineering, countermeasures have been elaborated to minimize residual risk and enhance integrity of the pipe.

Through this thesis work, the potential unsteady state conditions downstream in the event of emergency cases of an oil pipeline were analysed under various scenarios using the STONER PIPELINE SIMULATOR Software developed by the SPS Co. of United States, and mitigation measures are offered for the future works.

The BTC Pipeline now represents a pipeline system with the lowest possible level of risk rising from hydraulics. So for the pipelines which are supposed to be constructed in the future one should use similar programs as sophisticated as SPS and evaluate the results for a safe and economical operation.

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APPENDICES

BTC Crude Oil Pipeline Project Route