PIPELINE SURGE AKA WATER HAMMER

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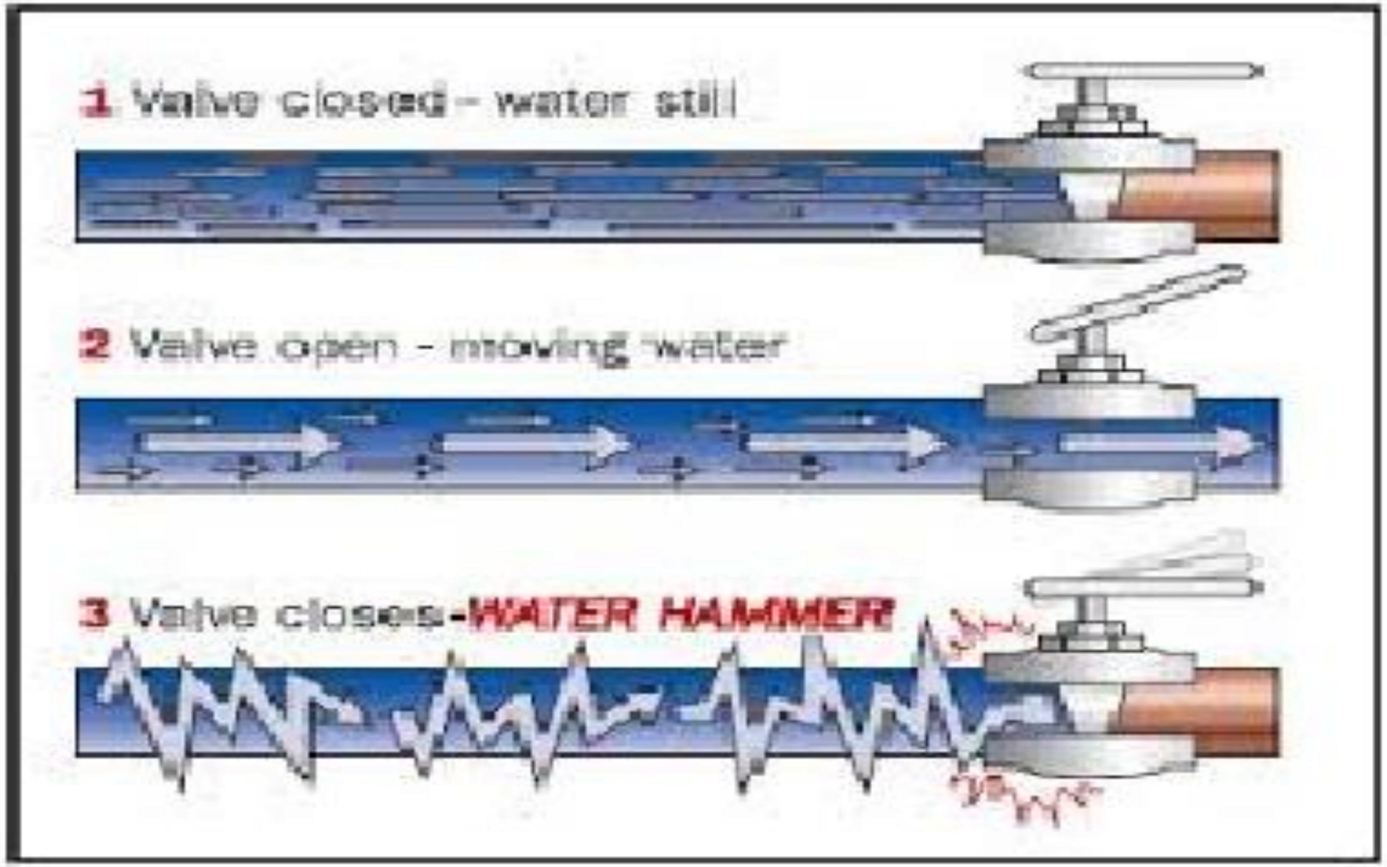
SURGE PHENOMENA – SIMPLISTIC DESCRIPTION

- Wikipedia provides a simplistic description as follows:

When a water pipe is suddenly closed at the outlet (downstream), the mass of water before the closure is still moving, thereby building up high pressure and a resulting shock wave. In domestic plumbing this is experienced as a loud banging resembling a hammering sound.

The common term “water hammer” derives its origin from this phenomena. In engineering terms this is described as surge.

SURGE – A PICTORIAL REPRESENTATION



SURGE IN A PIPE / PIPELINE - HISTORY

- It is an unsteady state of flow in a pipe or pipeline
- Unsteady state flow observations and analysis were first conducted in the mid-19th century
- Nicolai Joukowski, a Russian fluid dynamicist, and Lorenzo Allievi an Italian engineer are considered to be pioneers in developing the theory of water hammer
- Nicolai Joukowski was the first to demonstrate that pressure rise in a water line was directly related to the change in fluid velocity, the wave speed, and the fluid density. He is considered the father of water hammer analysis

SURGE IN A PIPE / PIPELINE – HISTORY (CONT.)

- In 1913, Lorenzo Alleivi created a mathematical and graphical treatment of water hammer that became the foundation for technical and analytical developments in the field for the next 50 years
- During the 1930’s and 1940’s graphical techniques were greatly improved. refinements in mathematical models allowed a more general form of basic equations to be used
- Development of high-speed computers in the 1960’s began a new era in hydraulic transient surge analysis. Analysis and studies that took weeks to perform could now be done in hours.
- Since the availability of high-speed computers enabling thousands of iterations of the transient phenomena of surge, surge analysis became an integral part of pipeline hydraulic studies

TERMINOLOGY IN PIPELINE SURGE ANALYSIS

- Surge Pressure: The rapid change in pressure as a consequence of a change in flow rate in a pipeline
- Wave speed: The velocity of sound in the fluid when flowing in a pipe, and is the speed at which surge pressures are transmitted along a pipeline. For water in very stiff pipes the sonic velocity could be as high as 1480 m/s
- Pipeline Period: The time required for a pressure signal to travel the length of the pipeline under surge analysis from one end to the other end and back again. The time is twice the length of the pipeline divided by the wave speed

TERMINOLOGY IN PIPELINE SURGE ANALYSIS (CONT.)

- ESD System: An emergency shutdown system which, initiated either manually or by automatic control sensors enables rapid and effective shutdown of pipeline operations in a safe and controlled manner
- Total Shutdown Time: The time required from manual or automatic initiation of ESD to final closure of ship or terminal manifold valves
- Total Valve Closure Time: The time required for a valve to move from a 100% open position to 100% closed (0% open) position

TERMINOLOGY IN PIPELINE SURGE ANALYSIS (CONT. 2)

- Effective Valve Closure Time: The time period over which an ESD valve reduces the flow from 90% of its steady state value to zero. The Effective Valve Closure Time is related to the total valve closure time as follows:
  - For gate valves the effective valve closure time corresponds to the last 5% valve opening to full valve closure
  - For butterfly valves the effective valve closure time corresponds to the last 15% valve opening to full valve closure
  - For ball valves the effective valve closure time corresponds to the last 25% valve opening to full valve closure
  - For plug valves the effective valve closure time corresponds to the last 30% valve opening to full valve closure

PIPLELINE SURGE OCCURRENCE – MOST PROBABLE CAUSES

- Pump Trip (power failure being the most common reason)
- Closure of an Automatic Emergency Shutdown Valve
- Sudden closure or opening of a manual or power (electric / pneumatic / hydraulic) operated pipeline process isolation valve
- Slamming shut of a Non-Return Valve

PIPELINE SURGE OCCURRENCE – POSSIBLE CONSEQUENCES

- Axial separation of flanges
- Pipe fatigue at welds
- Longitudinal splits of pipe
- Pumps knocked out of alignment
- Damage to piping and piping supports

The type and severity of the consequence depends on the magnitude of the surge pressure.

PIPELINE SURGE – COMMON CAUSES DESCRIBED

- Pump trip and subsequent sequence of events at rapid time intervals

  - Pump trips

  - Flow falls rapidly in the pipeline
  - The existing column of liquid in the pipeline continues forward under its own momentum
  - Upstream of the moving column a low-pressure region is created
  - After a time interval the forward moving liquid column is overcome by the opposing force of a static head
  - The liquid column now reverses and accelerates back towards the pump
  - In between the pump discharge NRV closes
  - The reversing liquid column now impinges on the closed NRV
  - The pressure rises rapidly (surge) in the pipeline
  - Factors that influence the initial pressure drop and the subsequent pressure rise are the initial pipeline velocity, the static head, the pipe length, material and friction in the pipe

JOUKOWSKI EQUATION FOR SURGE

- The maximum surge pressure is the sum of two components:
  - The instantaneous pressure increase at the moment of total flow blockage
  - The subsequent gradual pressure rise due to the line packing effect

$$P_S = \rho \times a \times \Delta v$$

where:
P_s = instantaneous surge pressure, Pa
ρ = liquid density, kg/m^3
a = pressure wave velocity, m/s
Δv = velocity change, m/s

JOUKOWSKI EQUATION FOR SURGE (CONT.)

- The wave velocity "a" is given by:

$$a = \sqrt{\frac{1}{\left(\frac{1}{K} + \left(\frac{d}{t_w} \times \frac{1}{E}\right)\right) \times \rho}}$$

where:

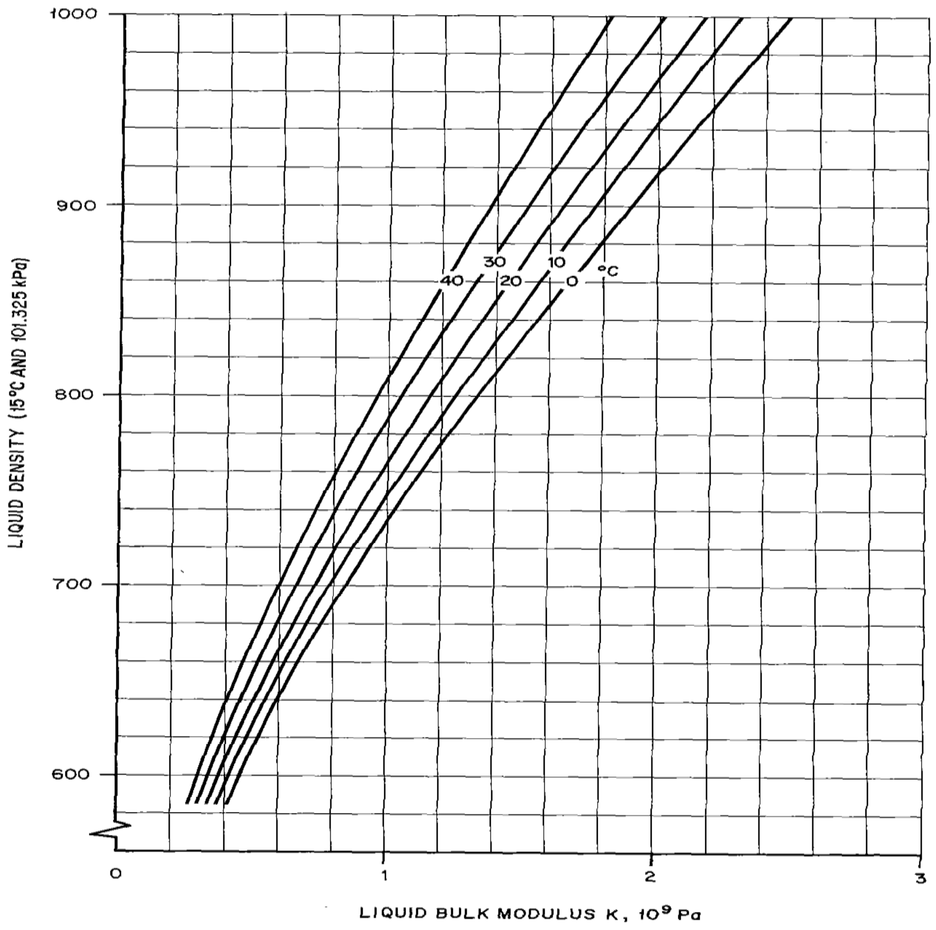
K = liquid bulk modulus, Pa (for water it is $2.2*10^9$ Pa)

d = pipe internal diameter, m

t_w = pipe wall thickness, m

E = Young's modulus of pipe material, Pa (for commercial steel it is $210*10^9$ Pa)

LIQUID BULK MODULUS OF HYDROCARBONS



(Source: API Std 1101, Measurement of Petroleum Liquid Hydrocarbons by Positive Displacement Meter, 1960/(ISO DIS 2714))

WHAT ABOUT SURGE IN GAS PIPELINES?

- Theoretically surge can occur in gas pipelines
- Looking at the Joukowski equation for surge pressure, density of the fluid has a major influence on surge pressure
- Gas densities are much lower in comparison to liquids. For example natural gas of MW 20 at a pipeline pressure of 60 barg and 30°C has a density of 56 kg/m^3 whereas a Natural Gas Liquid (NGL) at pipeline pressure and the same temp. would have a density of 790-830 kg/m^3
- Practically, surge analysis of gas pipelines is not considered due to the much smaller magnitude of gas density compared to liquids

SURGE DUE TO VALVE CLOSURE – DETAILED ANALYSIS

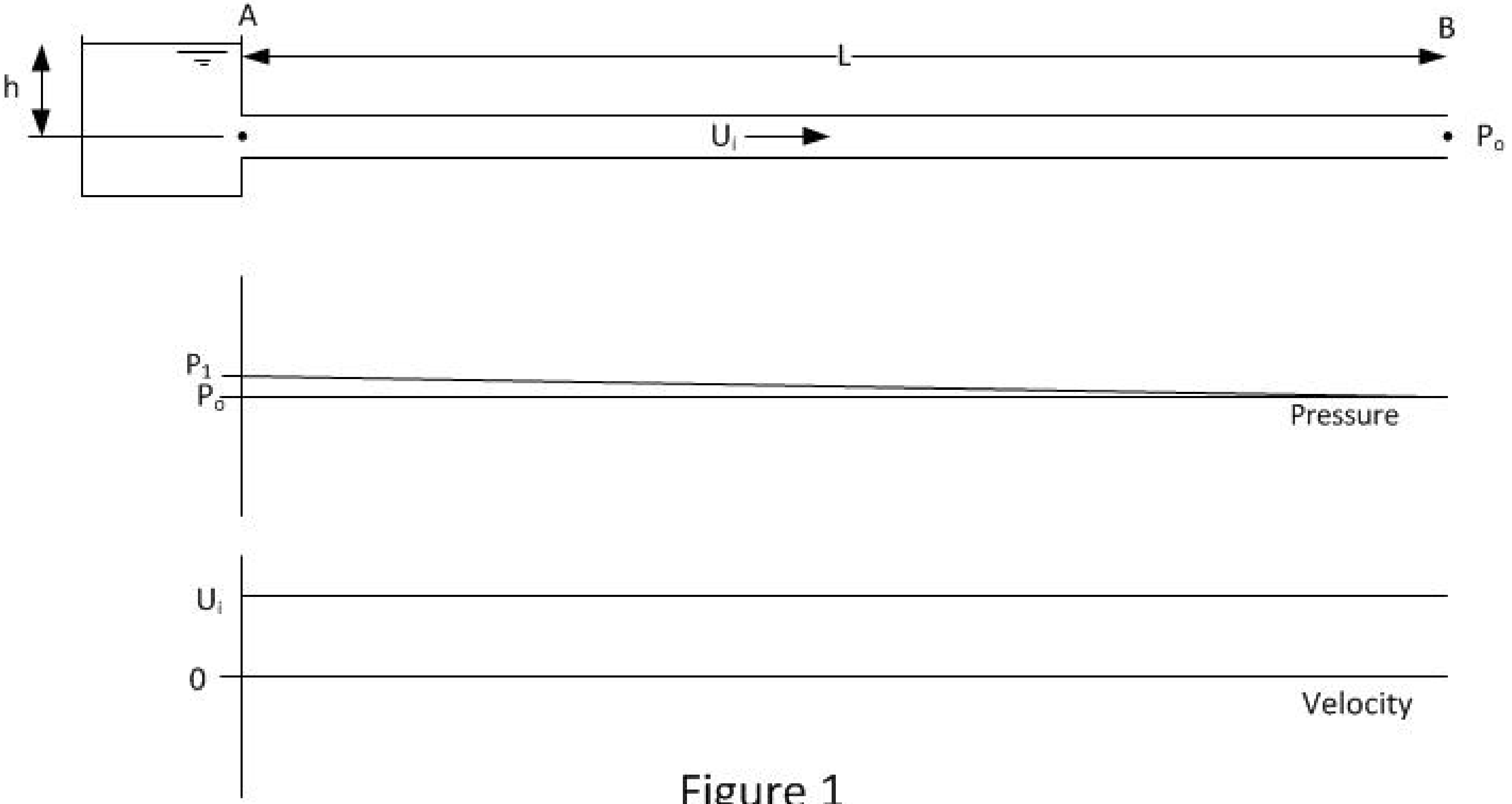


Figure 1

SURGE DUE TO VALVE CLOSURE – DETAILED ANALYSIS (cont.1)

Figure 1 shows the initial conditions in the pipe. The pipe inlet at position A is connected to a header tank which provides the pressure P_1 to drive the flow in the pipe. The other end of the pipe at position B is open to atmosphere and its pressure is P_0

$$P_1 = (\rho \times g \times h) + P_0$$

The length of the pipe is L

SURGE DUE TO VALVE CLOSURE – DETAILED ANALYSIS (cont.2)

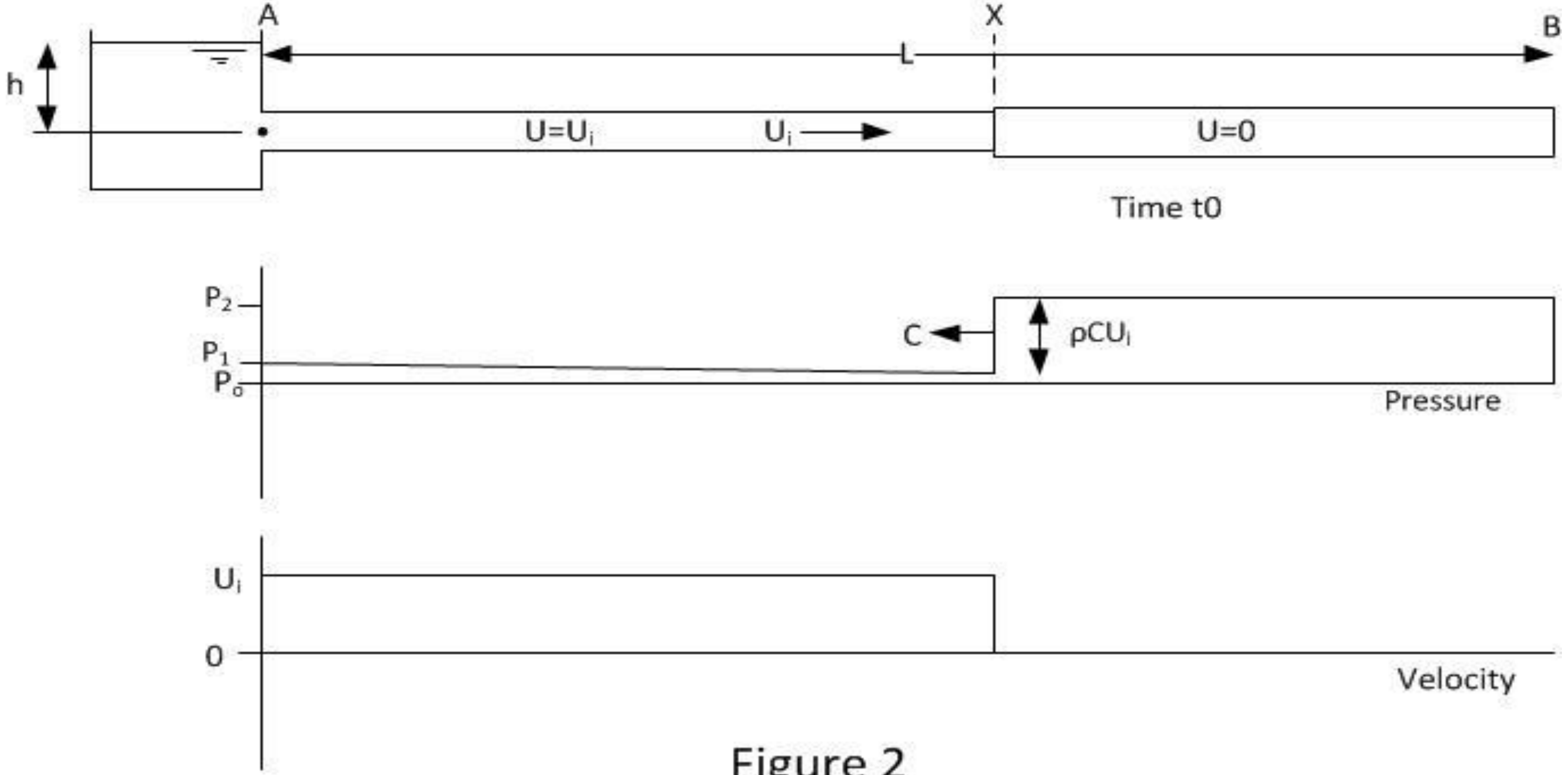


Figure 2

SURGE DUE TO VALVE CLOSURE – DETAILED ANALYSIS (cont.3)

Figure 2 shows the pipe and flow conditions just after the pipe end at B has been instantaneously closed at time t0. A pressure wave at position X is traveling **up** the pipe with velocity C (the sonic velocity). The pressure rise across the wave is ρCU (Joukowski equation). Upstream of position X the velocity is the initial velocity U_i. Downstream of X the velocity is 0.

SURGE DUE TO VALVE CLOSURE – DETAILED ANALYSIS (cont.4)

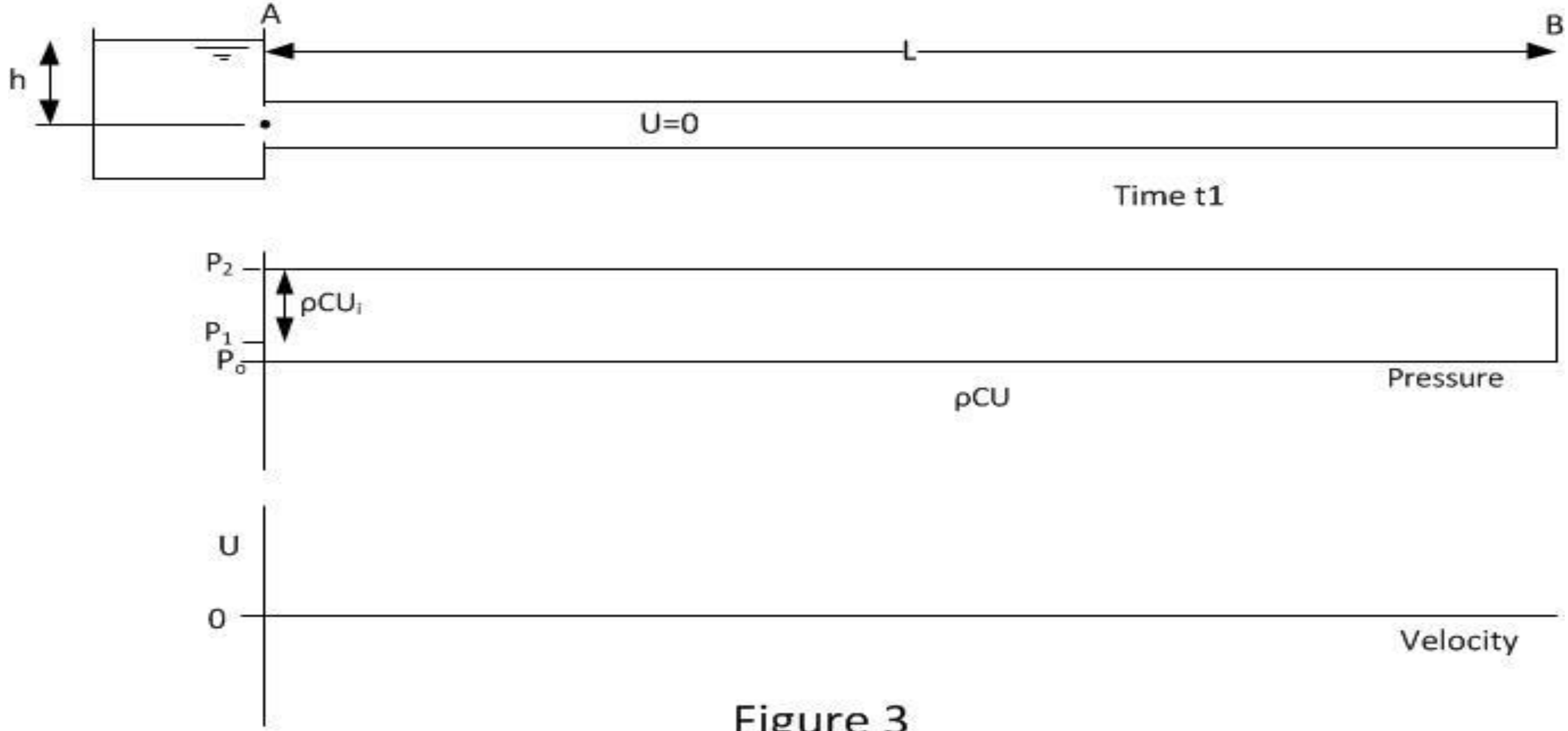


Figure 3

SURGE DUE TO VALVE CLOSURE – DETAILED ANALYSIS (cont.5)

Figure 3 shows the conditions when the pressure wave reaches position A at time t1. The pipeline pressure has been raised by $\rho C U_i$ and the fluid velocity is 0 throughout. This condition is unstable as the pipe inlet pressure is set by the head of fluid in the inlet tank h. So now the fluid needs to move in the reverse direction from the high pressure pipe into the lower pressure tank. This induces the first wave reflection and it occurs at time t1

Where:

$$t1 = to + \frac{L}{C}$$

SURGE DUE TO VALVE CLOSURE – DETAILED ANALYSIS (cont.6)

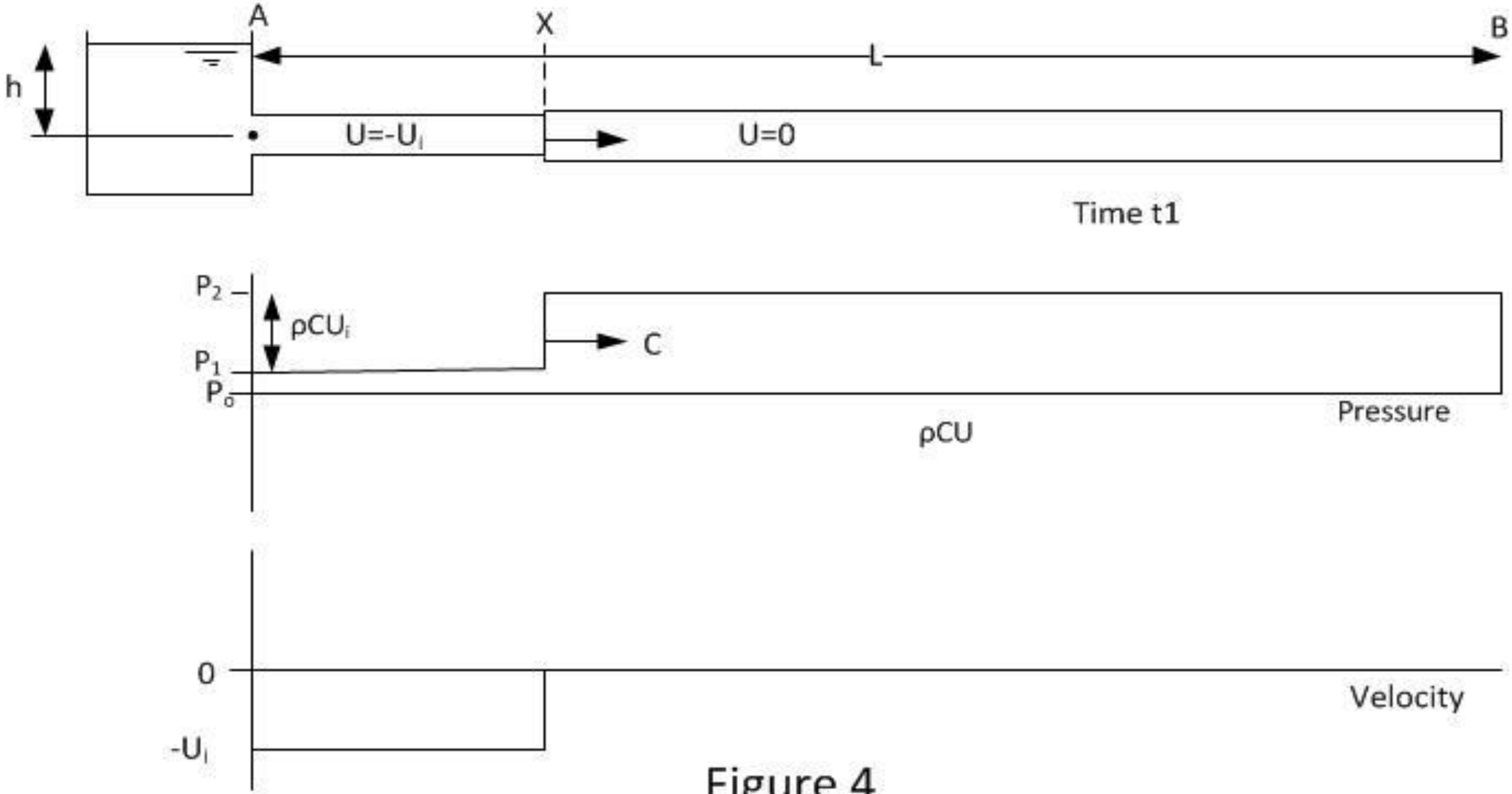


Figure 4

SURGE DUE TO VALVE CLOSURE – DETAILED ANALYSIS (cont.7)

Figure 4 shows the conditions after the first reflection. The pressure wave is at position X and is traveling **down** the pipe with velocity C. The fluid between positions A and X is traveling in the reverse direction with velocity $-U_i$. The drop in pressure across the wave front is $\rho C(-U_i)$.

SURGE DUE TO VALVE CLOSURE – DETAILED ANALYSIS (cont.8)

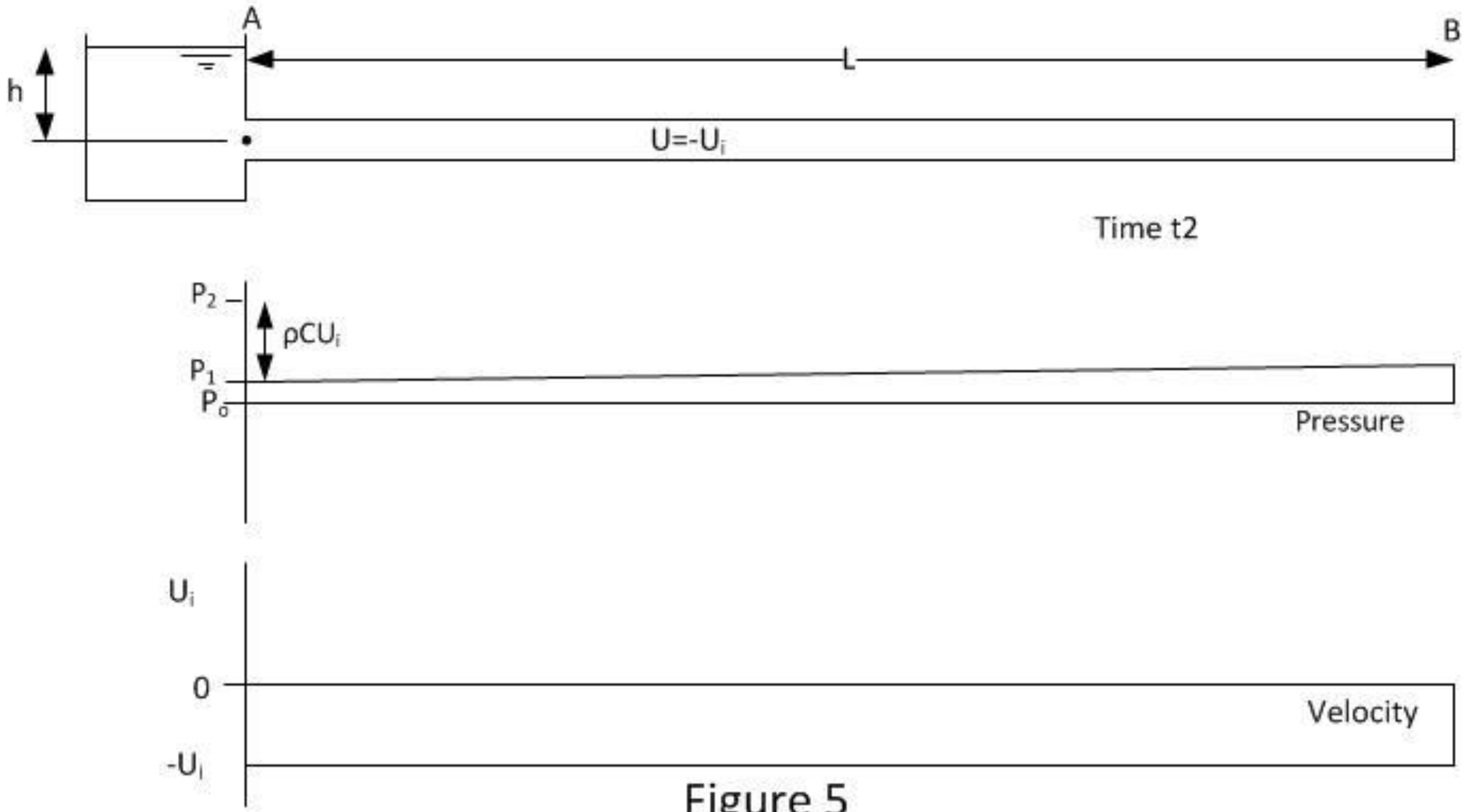


Figure 5

SURGE DUE TO VALVE CLOSURE – DETAILED ANALYSIS (cont.9)

Figure 5 shows the conditions when the pressure wave reaches position B at time t2. The whole of the pipeline pressure has been reduced and the fluid velocity is $-U_i$ throughout.

It should be noted there will be a small negative pressure gradient between A & B. This is required to overcome friction between the fluid and pipe as the flow is in the opposite direction. The magnitude of this pressure gradient will usually be significantly smaller than that generated by the change in velocity (Joukowski eqn). This friction gradient is exaggerated in the figure in comparison to water hammer effect for demonstration purposes.

As the end of the pipe at B is closed, this condition is unstable as there is fluid available to sustain the flow. This induces the second wave reflection at time t2.

Where:

$$t2 = t1 + \frac{L}{C} \quad \text{or} \quad t2 = t0 + \frac{2L}{C}$$

SURGE DUE TO VALVE CLOSURE – DETAILED ANALYSIS (cont. 10)

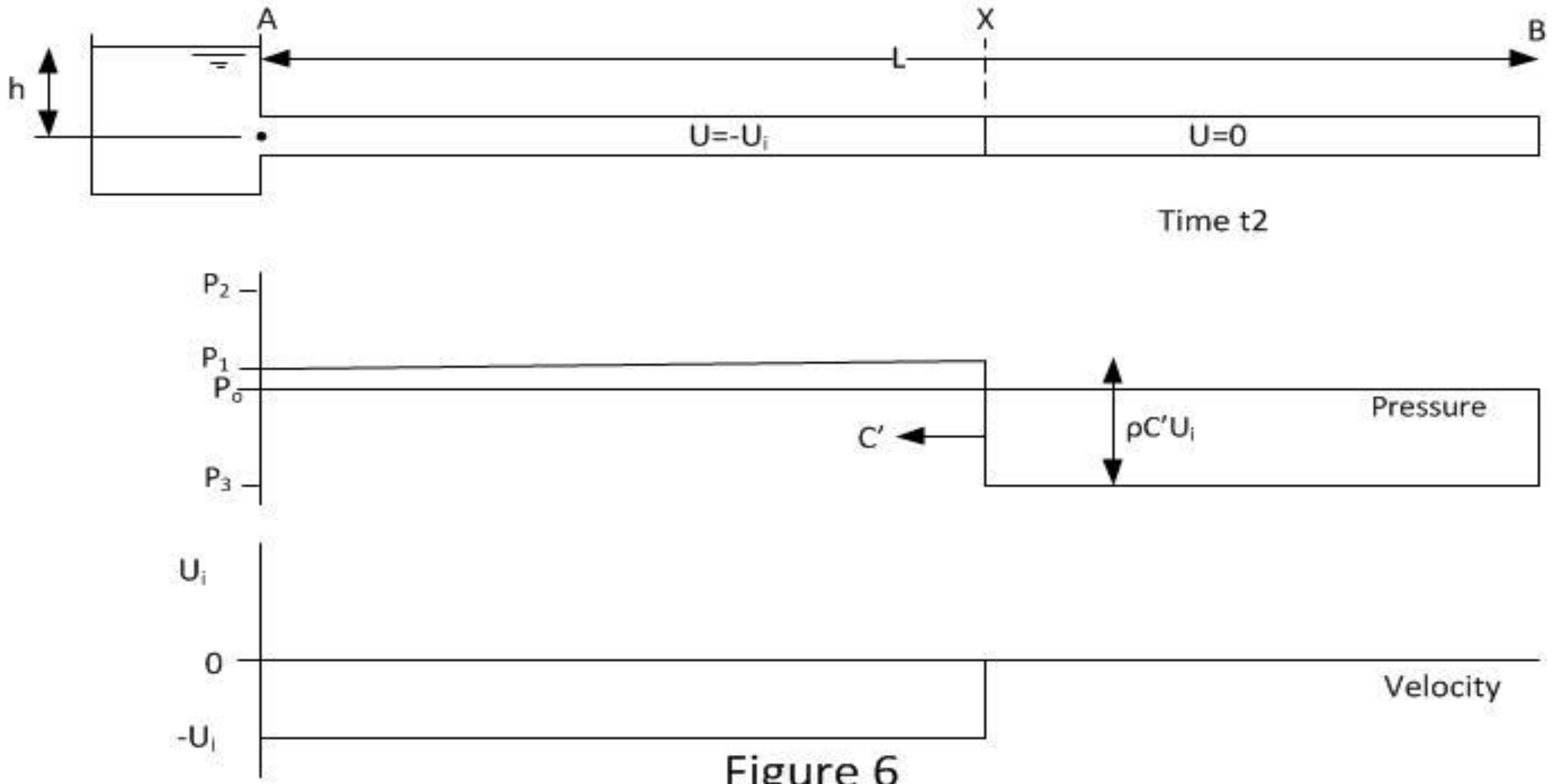


Figure 6

SURGE DUE TO VALVE CLOSURE – DETAILED ANALYSIS (cont. 11)

Figure 6 shows the conditions after the second reflection. The pressure wave is at position X and it is traveling **up** the pipe with velocity C’. The fluid between positions A and X is still traveling in the reverse direction with velocity $-U_i$. The fluid between X and B has been stopped.

The drop in pressure across the wave front is $\rho C'(-U_i)$. It should be noted that in this case the wave speed or sonic velocity has been changed from C to C’. C’ may be the same or less than C, it depends on the minimum allowable pressure P3.

The min. pressure in the pipe line can be ≥ vapor pressure of liquid. In the event pressure reduces to the vapor pressure, dissolved gas in the liquid will flash out of the liquid phase.

When cavitation occurs or dissolved gas comes out of liquid the bulk modulus of fluid is reduced from K to K’. It is this reduction in bulk modulus that allows the sonic speed to reduce from C to C’. Thus the magnitude of C’ will adjust its self so that P3 is not lower than min. possible pressure.

SURGE DUE TO VALVE CLOSURE – DETAILED ANALYSIS (cont. 12)

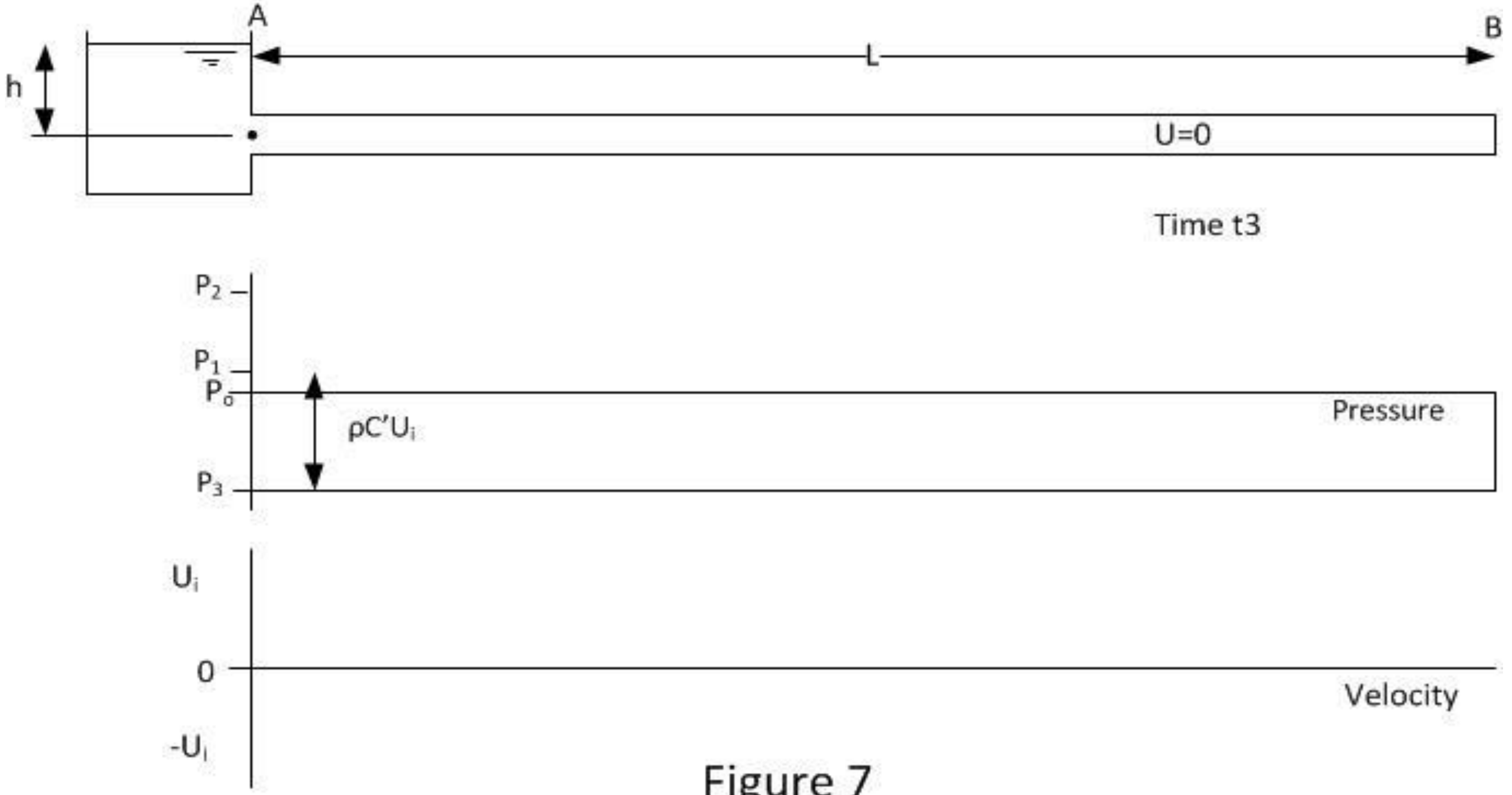


Figure 7

SURGE DUE TO VALVE CLOSURE – DETAILED ANALYSIS (cont. 13)

Figure 7 shows the conditions when the pressure wave reaches position A at time t3. The whole of the pipeline pressure has been reduced to P_3 and the fluid velocity is 0 throughout. This condition is unstable as the pipe inlet pressure set by the head of fluid in the inlet tank h is higher than the pipe pressure so now the fluid needs to move into the pipe from the header tank. This induces the third wave reflection and it occurs at time t3.

Where:

$t3 = t2 + \frac{L}{C'}$ or $t3 = t0 + \frac{2L}{C} + \frac{L}{C'}$

SURGE DUE TO VALVE CLOSURE – DETAILED ANALYSIS (cont. 14)

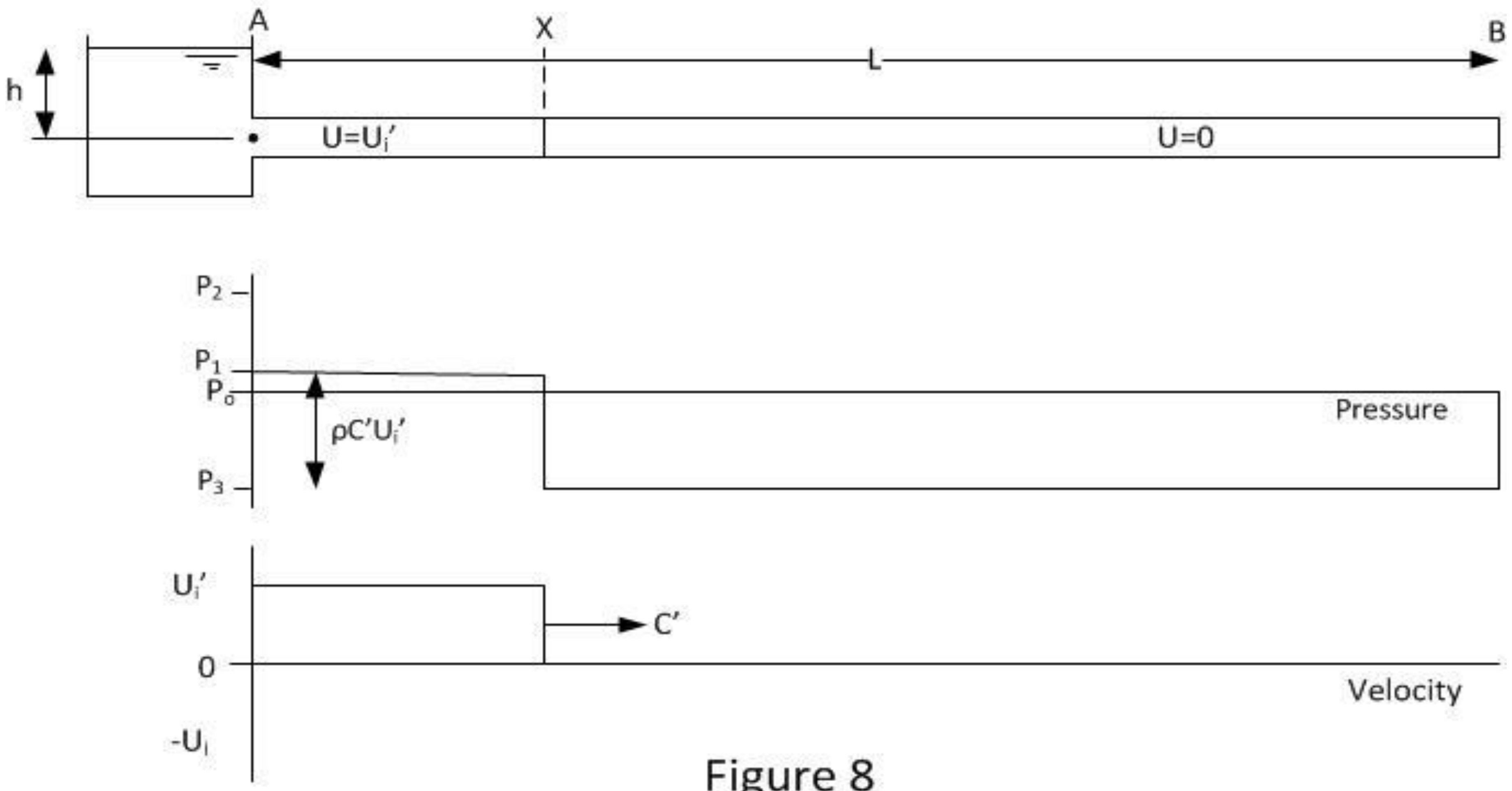


Figure 8

SURGE DUE TO VALVE CLOSURE – DETAILED ANALYSIS (cont. 15)

Figure 8 shows the conditions after the third reflection. The pressure wave is at position X, its traveling **down** the pipe with velocity C'. The fluid between positions A and X is still traveling in the normal direction with velocity U_i'. The fluid between X and B is stopped. The velocity in section A to X is shown as U_i' where U_i' is slightly less than U_i. By this stage the process has undergone 3 reflections and at every stage some energy is lost so over time the magnitude of the pressure waves and velocities are reducing.

The sonic wave velocity is still the reduced velocity C' as shown in figure 8. But if previously air or vapor had been liberated from the fluid then the vapor will be re-condense and gas bubbles will reduce in size and may start to go back into solution.

SURGE DUE TO VALVE CLOSURE – DETAILED ANALYSIS (cont. 16)

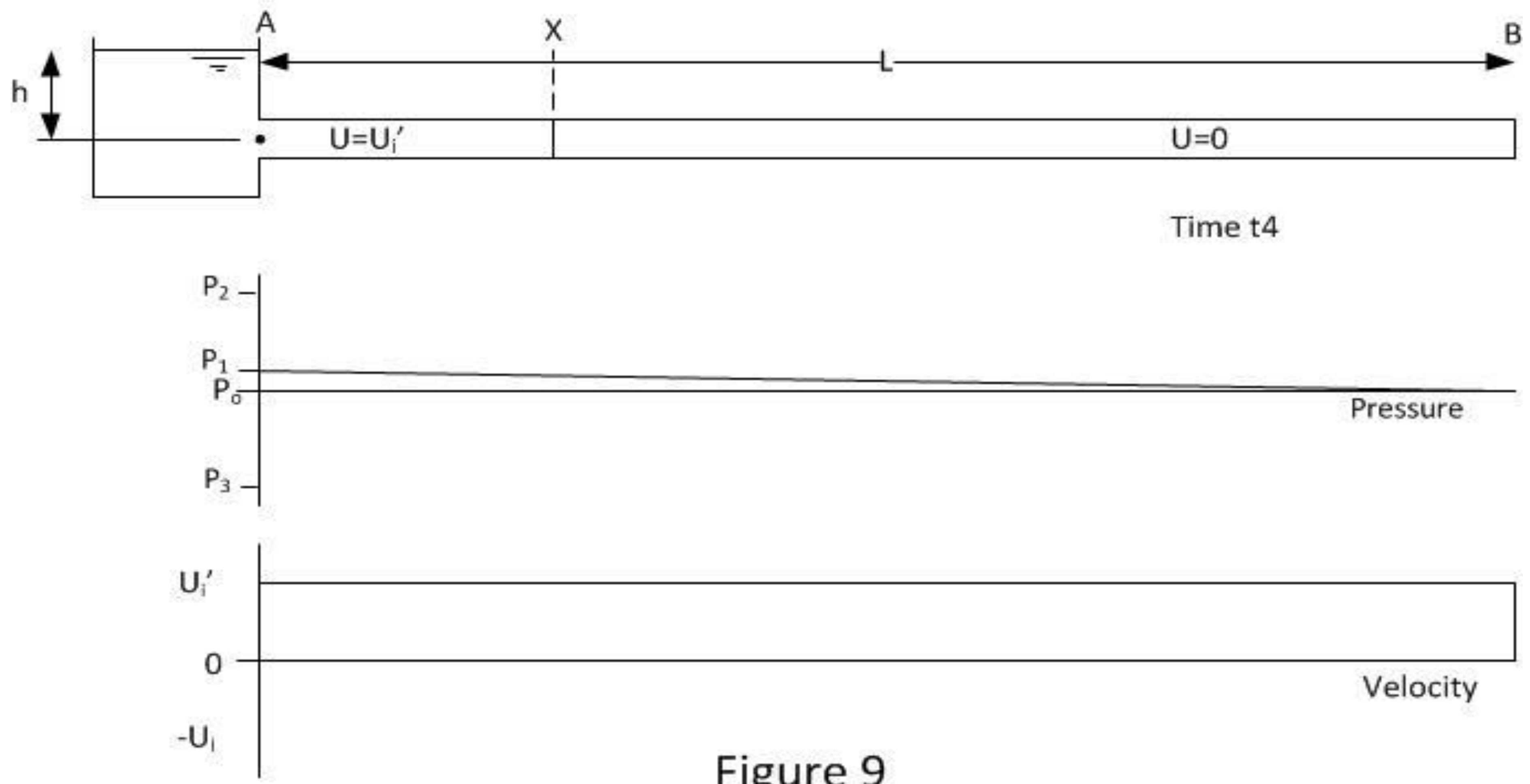


Figure 9

SURGE DUE TO VALVE CLOSURE – DETAILED ANALYSIS (cont. 17)

Figure 9 shows the conditions when the pressure wave reaches position B at time t4. As can be seen this is almost identical to the conditions shown in figure 1. The main difference is the velocity Ui' is a little lower than the original U_i. As the end of the pipe is closed there is nowhere for the fluid at B to go. So this will induce the final reflection at time t4 and then the whole process is repeated.

Where:

$t4 = t3 + \frac{L}{C'}$ or $t4 = t0 + \frac{2L}{C} + \frac{2L}{C'}$

SURGE DUE TO VALVE CLOSURE – DETAILED ANALYSIS (cont. 18)

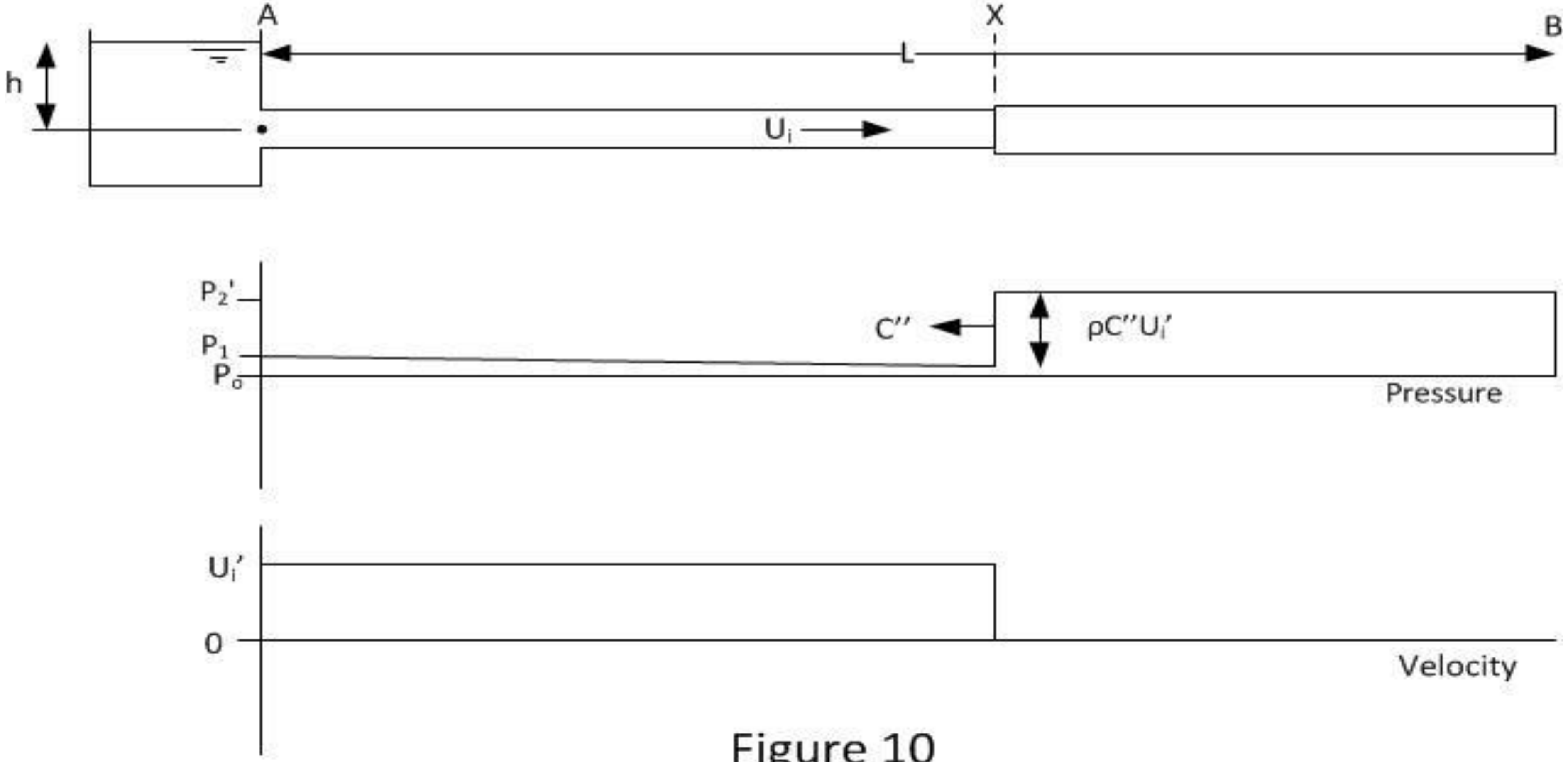


Figure 10

SURGE DUE TO VALVE CLOSURE – DETAILED ANALYSIS (cont. 19)

Figure 10 shows the condition after the fourth reflection. The cycle has now began to repeat however the water hammer pressure is now reduced a little from P_2 (figure 2) to P_2'. This reduction in pressure has two causes. The fluid velocity has been reduced due to energy losses.

The sonic velocity C'' may be less than the original sonic velocity C. If during the previous stages shown in figures 8 and 9 any gas was liberated from the liquid then this gas volume will have been reduced, however it takes time for the gas to be completely reabsorbed so there are likely to be small residual gas bubbles in the fluid. These gas bubbles will reduce the fluid bulk modulus thereby reducing the sonic speed.

Over a number of cycles the surge will eventually stop. The pipe pressure will end up at P1 and the flow will stop oscillating.

WHAT CAN BE DONE TO PREVENT SURGE?

- Complete computer modeling of pipeline profile during the design stage, to determine the effects of unsteady flow of liquids in transmission pipelines
- Stage pumps shutdown sequence, in conjunction with the closing of main pipeline valves
- Linked ship/shore emergency shutdown (ESD—for loading and off-loading tankers): historically, if the tanker’s ESD valve shut in, the pump continued to operate for a period of time after the valve closure, causing surge pressure conditions. A linked ESD system should be provided to initiate the ESD on board the tanker to trip the pumps. The ESD valve closure time allows the pipeline flow to decay. These systems must ensure the transfer pump is shutdown first.
- Staged ESD or motor operated valve closure times; extending the valve closure time will help reducing the surge effect.

SURGE MITIGATION AND PROTECTION METHODS

- Operating Procedures

  - Keeping in view the possible surge scenarios during pipeline operations prepare “Standard Operating Procedures” (SOPs) which do not allow surge conditions to develop

- Slow Valve Closure

  By closing a valve over a sufficiently long period the surge pressure generated may be significantly reduced. This also allows more time to trip the pumps and hence reduce the maximum pressure. This can be implemented either by slowing down the valve actuator or by installing a 2-speed actuator which reduces the valve closure speed over the (critical) last 10-20% of the valve’s travel.

  As a thumb rule valve closure for automatic shutdown valves is 1 inch per second. As an example, if the valve size is 10 inch, then the valve should not close faster than 10 seconds. If a surge analysis study predicts slower valve closure time to prevent high surge pressures, then the same should be applied instead of the thumb rule. Generally for valve sizes above 12 inch the valve closure time of 15 seconds minimum is considered and can go up to 30-60 seconds depending on the surge study recommendations

  Closure times need to be defined by process engineers in the automatic shutdown valve process data sheet.

SURGE MITIGATION AND PROTECTION METHODS (cont.)

- Installing a Surge Pressure Relief System

If the creation of an unacceptable pressure surge cannot be avoided by slow valve closure a pressure relief system can be installed as near to the point of surge origin as practically possible. The system would vent a quantity of product from the pipeline once a pre-set pressure limit is exceeded thereby limiting the final surge pressure.

The fundamental requirements of surge relief systems include the need for fast acting, high capacity valves which can open very quickly to remove surge pressures from the line and then return to the normal (closed) state quickly but without causing additional pressure surge during closure. These valves are often required to open fully in very short periods of time, so that they may pass the entire flowing stream if conditions dictate.

SURGE MITIGATION AND PROTECTION METHODS (cont. 2)

- Installing a Surge Pressure Relief System (cont.)

In normal conditions, surge relief valves are closed, when a surge event interrupts normal steady-state flow, the fluid pressure exceeds the valve set point and the valve automatically and immediately opens, relieving sufficient liquid volume through a relief line to a surge tank to eliminate the surge. As the surge is dissipated, the valve closes again without slamming shut. It is then ready to act again upon any subsequent surge. In this way, the line is constantly protected from the buildup of pressure surges.

- Non-Slam Non-Return (Check) Valves

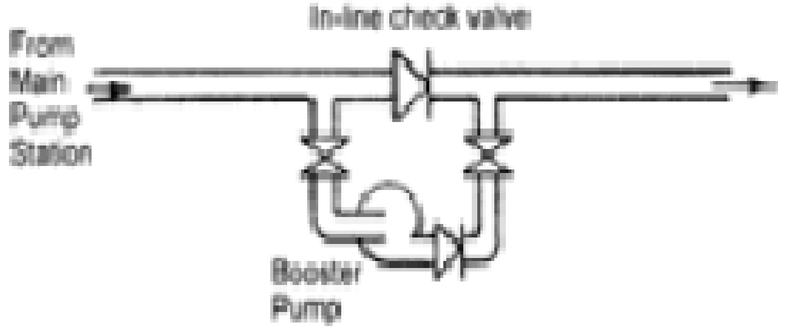
The type of NRV used in a pipeline system has a great bearing on surge pressures that can occur in the pipeline system. Non-Slam NRVs are fast-closing valves that reduce surge pressure at pump. The conventional swing and tilted disk NRVs are unsuitable in high-head pipeline applications. The nozzle type check valve fulfills the design criteria of a non-slam, fast-closing NRV.

SURGE MITIGATION AND PROTECTION METHODS (cont. 3)

- Bypass Check Valves

Bypass valves take the form of a valve in parallel to the pumps. The concept is that on pump trip (power failure) there is still a reduced flow into the pipeline through this valve. This prevents the column separation occurring immediately after the pump discharge check valve.

These bypass check valves are used for pumping from above-ground tanks providing enough static head to allow flow through such valves. Another application is where there is a booster pump in the pipeline. The bypass valve opens and thus protects the pipeline from surge pressures when the booster pump fails



RELIEF VALVES FOR SURGE PROTECTION

- Main Requirements for Surge Pressure Relief Valves

  - Fast Acting

  - High Capacity

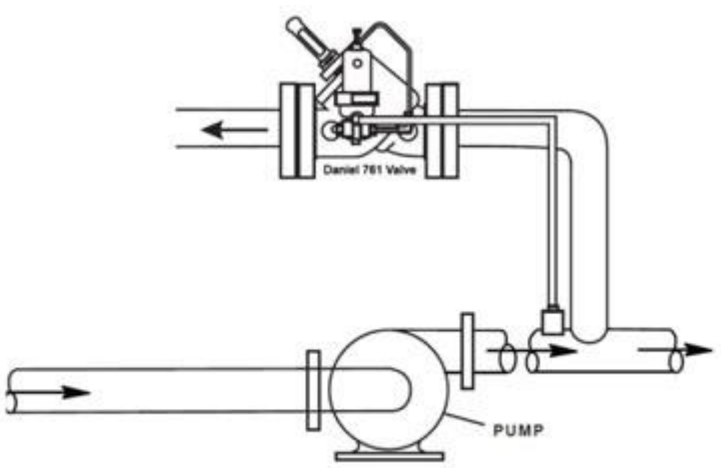
- Relief Valves Meeting the above requirements

  - Pilot Operated

  - Gas-loaded

PILOT-OPERATED SURGE RELIEF VALVE

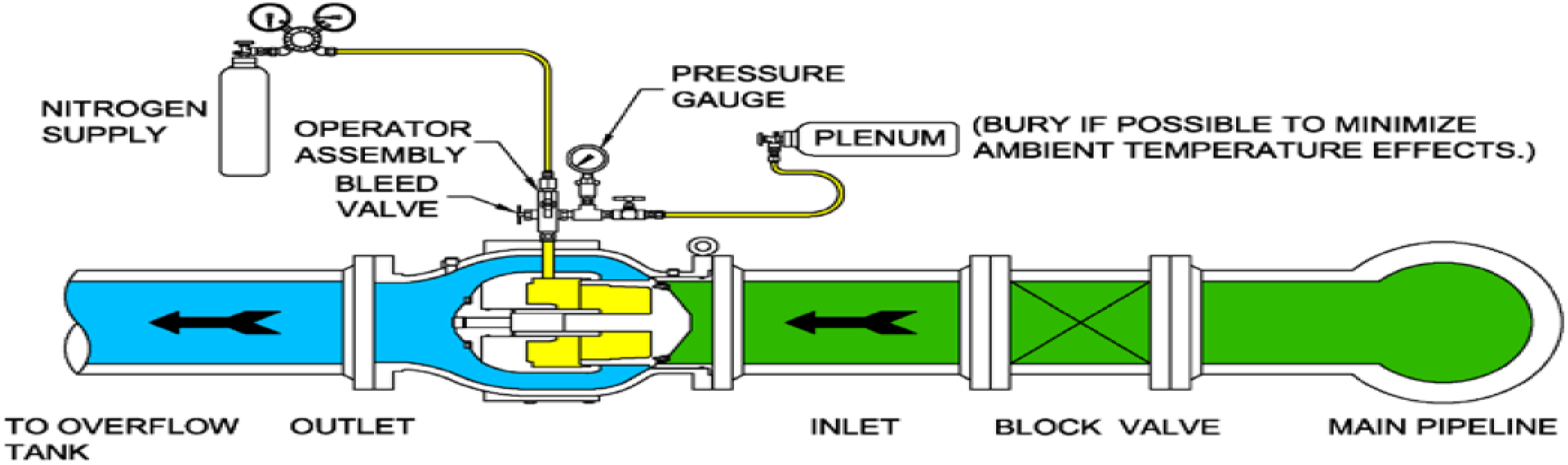
- Can control pressures to within +/- 2 psi
- Relatively slower response time when compared to Gas-Loaded
- Recommended only for clean and low viscosity fluids



Pilot-Operated Surge Relief Valve

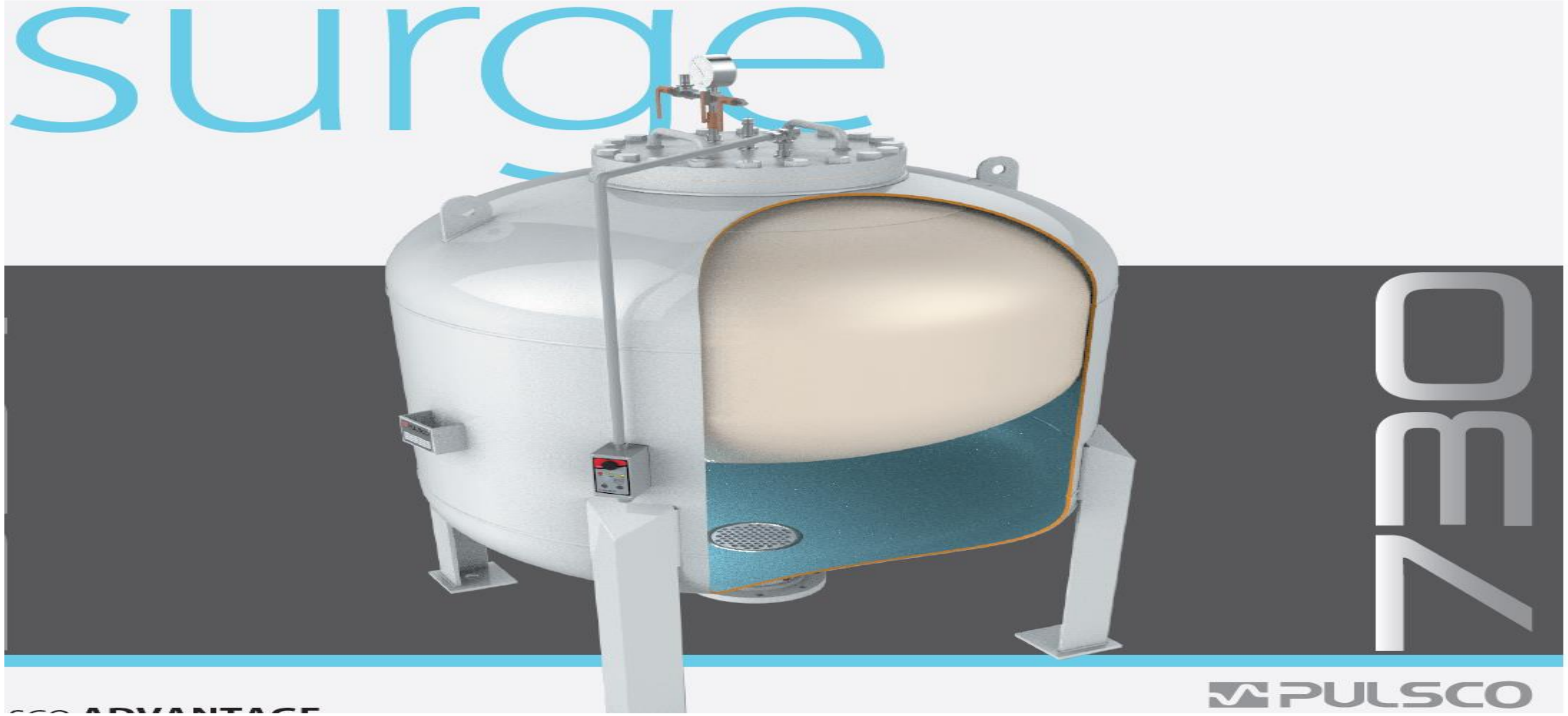
GAS-LOADED SURGE RELIEF VALVE

- These are quick-opening and provide full opening
- Nitrogen is commonly used to pressurize the valve piston
- Nitrogen pressure is maintained at the valve set pressure by regulator
- Nitrogen buffer vessel holding the Nitrogen to be kept insulated to minimize temperature changes and thermal expansion which can change the set-point of the relief valve



GAS ACCUMULATORS FOR SURGE PROTECTION

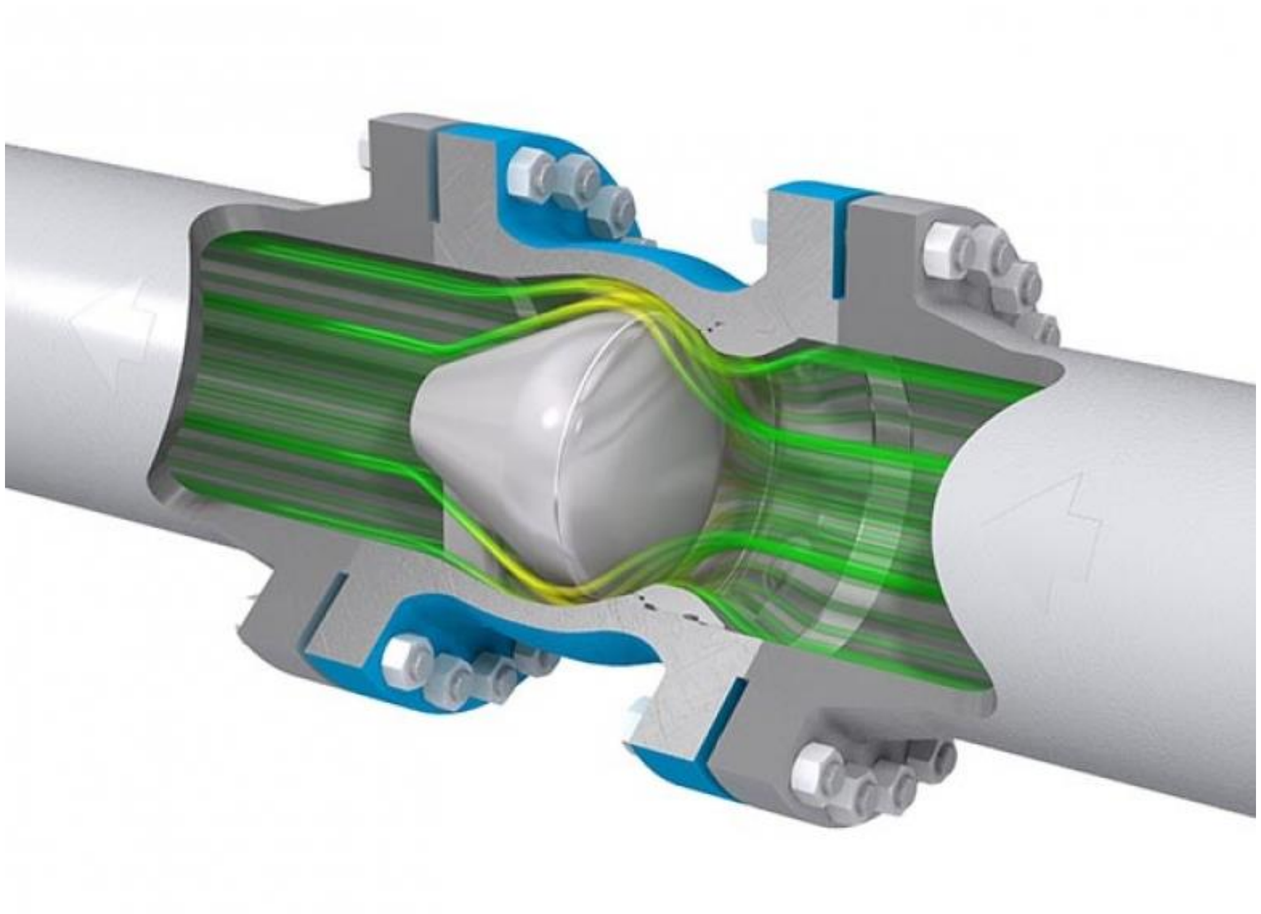
- Particularly effective in pump trip conditions where a negative pressure wave develops immediately downstream of the pump NRV
- Residual pressure in the gas accumulator reduces the deceleration of the liquid column and prevents column separation and negative pressures
- These can be rigorously modeled using surge analysis software



NOZZLE TYPE CHECK VALVE FOR SURGE PROTECTION

- These fulfill the criteria of fast-acting and non-slam action for pipeline surge mitigation
- “Mokveld” and “Noreva” are the technology leaders in nozzle type check valves
- Both of these manufacturers provide nozzle check valves with low pressure drops and low friction parts to prevent valve getting stuck up in either the open or closed position
- Data for deceleration versus maximum velocity can be provided by Mokveld and Noreva
- For a more complete understanding of the behavior of check valves and their relationship to pipeline surge engineers are advised to refer the book: Fluid Transients in Pipeline Systems by A. R. D. Thorley
- Nozzle check valves may be unsuitable for dirty service which may clog the nozzle

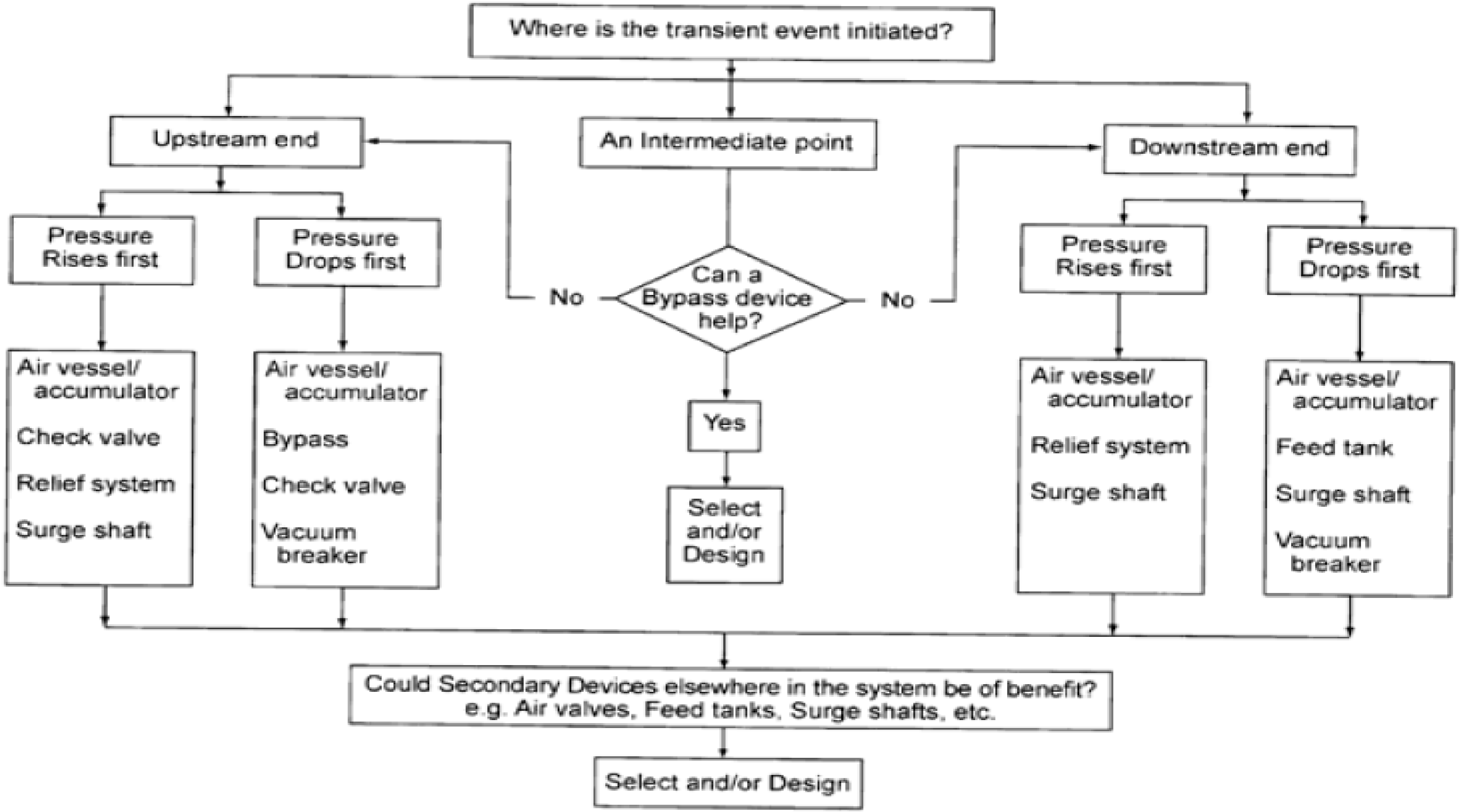
MOKVELD NON SLAM CHECK VALVE



NOREVA NON-SLAM AXIAL NOZZLE CHECK VALVE



SELECTION FLOW CHART FOR SURGE MITIGATION DEVICES



QUIZ

Q1 Who are considered the pioneers in Surge Study?

QUIZ

A1 Nicolai Joukowski and Lorenzo Allievi

QUIZ

Q2 What is effective closure time for a shutdown valve?

QUIZ

A2 The time period over which the shutdown valve reduces the flow from 90% of its steady state value to zero

QUIZ

Q3 Why surge analysis for gas pipelines is normally not considered?

QUIZ

A3 Because of the low density of gases compared to liquids

QUIZ

Q4 What is the thumb rule for closure time of automatic shutdown valves?

QUIZ

A4 1 inch per second based on valve size in inches


THANK YOU FOR WATCHING
I HOPE YOU ENJOYED THE PRESENTATION