Antamina's Copper and Zinc Concentrate Pipeline Incorporates Advanced Technologies

Ron H. Derammelaere and Dr. George Shou
Pipeline Systems Incorporated, USA

ABSTRACT

East of Huscaran National Park, in the Peruvian Andes, is the Antamina Mine. A 302-km-long slurry pipeline, commissioned in July 2001, transports concentrates of copper and zinc, as separate batches, from an elevation of 4,200 m to sea level.

Antamina's pipeline incorporates many new technologies. High-pressure PD pumps, high-pressure pipeline with HDPE lining, high-headloss adjustable choke stations, durable ceramic chokes, comprehensive computer simulation, computer-based batch tracking, leak detection and operation advisory, and trail-out prediction are among them. This paper addresses primarily the technical challenges in preventing slack flow and over-pressure in the pipeline while batches (copper slurry/water/zinc slurry) of significantly different densities move through the pipeline in mountainous terrain.

1 INTRODUCTION

Pipelines have become an important and cost-effective means of transporting solids over long distances. Slurry pipelines are particularly competitive when the process used in beneficiation, or downstream processing, is in slurry form and requires a particle size suitable for economic pipeline transport. This scenario exists in the production of base metal minerals (copper, zinc, iron, etc.).

The technical and economical feasibility of slurry pipelines was first demonstrated over 40 years ago with the Consolidated Coal pipeline in Ohio (1956), which forced rail rates down and saved the electric utility over $5 million a year. Since then, dozens of long-distance pipelines (i.e., each several hundred kilometers long) have been developed commercially, with many still operating.

The copper industry, in particular, has used slurry pipelines for long-distance and cross-country transportation of concentrates. There are fourteen high-pressure copper concentrate slurry pipelines in operation, some as long as 300 km. The longest and largest of these was recently constructed in South America, to move copper and zinc concentrate from the mine site, at elevations as high as 4,200 meters, to sea level.

In each of these projects, alternate transportation modes – such as trucking – were evaluated as part of the feasibility study. While requiring greater initial capital investment than trucking, pipelines were found to be ultimately more economically attractive, more reliable, and to have a lesser environmental impact than other modes of transportation.

Antamina is the latest project to come "on line," starting commercial operation on July 1, 2001. Table 1 compares the Antamina pipeline with other major concentrate pipelines constructed in South America in the past decade.

Table 1: Summary of Andean Copper Concentrate Slurry Pipelines

Name Location	Length (km)	Diameter (mm)	Through-Put, mtpy	No. of Pump Stations	No. of Choke Stations	Elevation Of Pump Station 1, m	Year of Operation
Escondida, Chile	167	152 - 229	2	1	2	3060	1990
Los Bronces, Chile	57	610	12	0	3	3300	1992
Alumbrera, Argent.	312	152	0.9	3	2	2400	1997
Collahuasi, Chile	203	178	1	1	3	4300	1998
Los Pelambres, Chile	120	194	1.1	1	1	1610	1999
Antamina, Peru	300	219 - 273	1.5	1	3	4200	2001

In addition to the typical technical challenges of designing and building a slurry pipeline through rugged terrain, the Antamina pipeline must transport multiple products: zinc and several grades of copper. Minimizing the cross-contamination between the products is an important technical issue. This subject will be briefly discussed in one of the following sections, but is addressed in more detail in another paper to be presented at this conference.

Inserting water batches between the slurry batches to mitigate possible cross-contamination requires more complex operating procedures. The densities of the copper and zinc slurries are approximately twice that of the adjoining water, and conditions of slack flow (partially filled pipe) and over-pressure (pressure exceeds pipe allowable) can develop as the interfaces move through the pipeline in mountainous terrain. Both conditions are detrimental to the integrity of the pipeline but can be prevented with adjustable energy dissipation (choke) stations and careful operation of the pipeline.

Section 3 describes the use of the hydraulic grade line (Bernoulli equation) to graphically show slack flow and over-pressure conditions, and how it is used for operator training in the Pipeline Simulator™.

2 ANTAMINA PIPELINE SYSTEM

The Antamina slurry pipeline system consists of a pump station at the mine site connected to the terminal station at Huarmey via a 302-km pipeline. Between these two stations, intermediate station installations (consisting of four valve stations and four pressure monitoring stations) have been positioned to limit the static head, provide choking, and monitor pressure.

2.1 Pump Station - PS1

Concentrate is stored in five, 18 m x 18 m agitated storage tanks. Two tanks are dedicated to zinc concentrate and three to copper (high and low bismuth). This amount of storage is necessary to accumulate one type of concentrate while the other is being pumped. When the tank of the concentrate being pumped (e.g., copper) is empty, the pump station operator switches to water and continues to pump water for a minimum of one hour before starting the next concentrate batch (e.g., zinc).

Figure 1: Pump Station PS1

The pump station (Figure 1) has four positive displacement 1,300 kW (piston) mainline pumps (three in operation and one on stand-by). Two to three pumps in parallel will provide the necessary discharge head and flow to transport concentrate from the concentrator to the terminal station. Normal throughput is approximately 250 tons per hour (tph) but the system is capable of operating at 350 tph.

The maximum discharge pressure for the selected pipeline route is 24.5 MPa (3,550 psi). The discharge flange rating of the pump station is 1500# ANSI (25.9 MPa or 3,750 psi, at ambient temperature rating). The station suction piping pressure rating is ANSI 150# (680 kPa or 100 psi).

2.2 Pressure Monitoring Stations - PMS 1, 2, 3, and 4

Pressure monitoring stations are utilized to measure pressures along the pipeline and to maintain optimized pipeline slurry flow conditions (e.g. avoid slack flow) and to provide input into the leak detection system.

2.3 Valve Station – VS1, 2 , 3, and 4

Four intermediate valve stations were installed to segment the pipeline during shutdown on slurry. The valve stations utilize valves positioned in tandem with one valve to take the wear caused by opening and closing under the differential pressures and high velocity conditions and the other to seal (isolate) once the pressures and velocities have been reduced.

Figure 2: Valve Station 1/Choke Station

Two of these stations also have choking facilities. Both provide back-pressure necessary to prevent slack flow in the pipeline for minimum slurry flow conditions. Each choke can generate approximately 50 meters of headloss. Choking requirements change constantly as slurry/water interfaces move through the pipeline.

Pressure instruments, upstream and downstream of the choke banks, are used to control and monitor choke wear.

2.4 Terminal - T1

The terminal station contains block valves, to prevent drain down of the upstream section of the pipeline, and chokes for back-pressure control.

Slurry is directed into distributor boxes which send slurry to any of the four slurry tanks (each 15m x 15m).

2.5 Pipeline

The pipeline is 302 km in length and traverses diverse terrain conditions from high mountainous areas to desert like conditions along the coastal sections. From the pump station to VS1, the pipeline diameter is 273 mm OD, from VS1 to VS4, 219 mm OD, from VS4 to km 213, 244 mm OD, and the balance is 273 mm OD. To allow smooth restart after shutdown with slurry, the slope of the pipeline has been limited to 15%. Slurry flows in the pipeline at velocities from 1.5 m/s to 3.1 m/s.

The pipeline was manufactured from API 5L Grade X65, carbon steel and is lined with high-density polyethylene (HDPE) for protection against internal corrosion. The pipeline was constructed by buttwelding the pipe sections together. Flanged joints (ANSI 1500#) were spaced at 400 to 1,200 meters for the HDPE liner insertion process.

The pipeline piping and components were designed and constructed in accordance with ANSI B31.11. All pipeline welds were ultrasonically tested and each flanged section was individually hydrotested.

2.6 SCADA/Telecom System

A supervisory controls and data acquisition (SCADA) system is utilized to control and operate the pipeline. This system operates over the fiber optic cable telecommunications system installed parallel to the pipeline. The SCADA system includes the Pipeline Advisor™, which displays the profile, a real-time hydraulic gradient, and advises the operator of potentially critical situations, such as slack flow or overpressure. This will provide the operator's indication to increase or decrease the number of chokes, or adjust pump speed, etc.

3 HYDRAULIC GRADE LINE (HGL)

Discussions in this paper relating to slack flow, over-pressure, and batch hydraulics require an understanding of the hydraulic grade line. It is also the basis for operator training and an excellent visual tool to assess the operating limits of the pipeline.

The energy line is a graphic representation of Bernoulli's equation, expressed in meters of column height of that particular liquid. The total energy, also referred to as total head (H), is made up of three components: the potential head, or height of the pipeline above sea level (Z); the static head, which is a function of the pressure and the density of the liquid in the pipeline (p/γ, or pressure expressed in meters of fluid); and the dynamic head, a function of velocity ($v^2/2g$):

$$H = p/\gamma + v^2/2g + z \text{ (energy line)}$$

When plotted as a function of pipeline distance, the total head in meters of liquid is a straight sloped line, assuming a constant pipe diameter and constant liquid density in steady state. The slope of the line represents the loss of head (friction) in the pipeline.

Since, in most pipelines, the dynamic head is negligible, this term is eliminated from the equation, and the remaining terms represent the hydraulic grade line, sometimes referred to as the piezometric headline:

$$H = p/\gamma + z \text{ (hydraulic grade line)}$$

When superimposing the pipeline terrain profile (or potential head Z) on the same plot, the distance between the profile and the hydraulic grade line conveniently represents the pressure in the pipeline expressed in meters of that fluid. Therefore, if fluids of different densities (say, slurry and water) are in the same pipeline, at the interface of the two liquids, a discontinuity will appear in the hydraulic gradient. This is because, on one side of the interface the pipeline pressure is expressed in meters of slurry, while on the other side of the interface it is expressed in meters of water.

Another set of lines shown on the same graph represent allowable head for steady-state and for transient conditions. These lines are also plotted in meters of fluid, and therefore, will also show a discontinuity at the interface of two batches. For proper operations, the hydraulic gradient must always stay in the area between the allowable headlines and the profile. If the hydraulic grade line intersects the allowable headlines, the pipeline is over-pressured, and if the hydraulic grade line intersects the profile, the flow will go slack (i.e., partially filled pipe). Figure 3 shows commonly used definitions in slurry pipeline engineering.

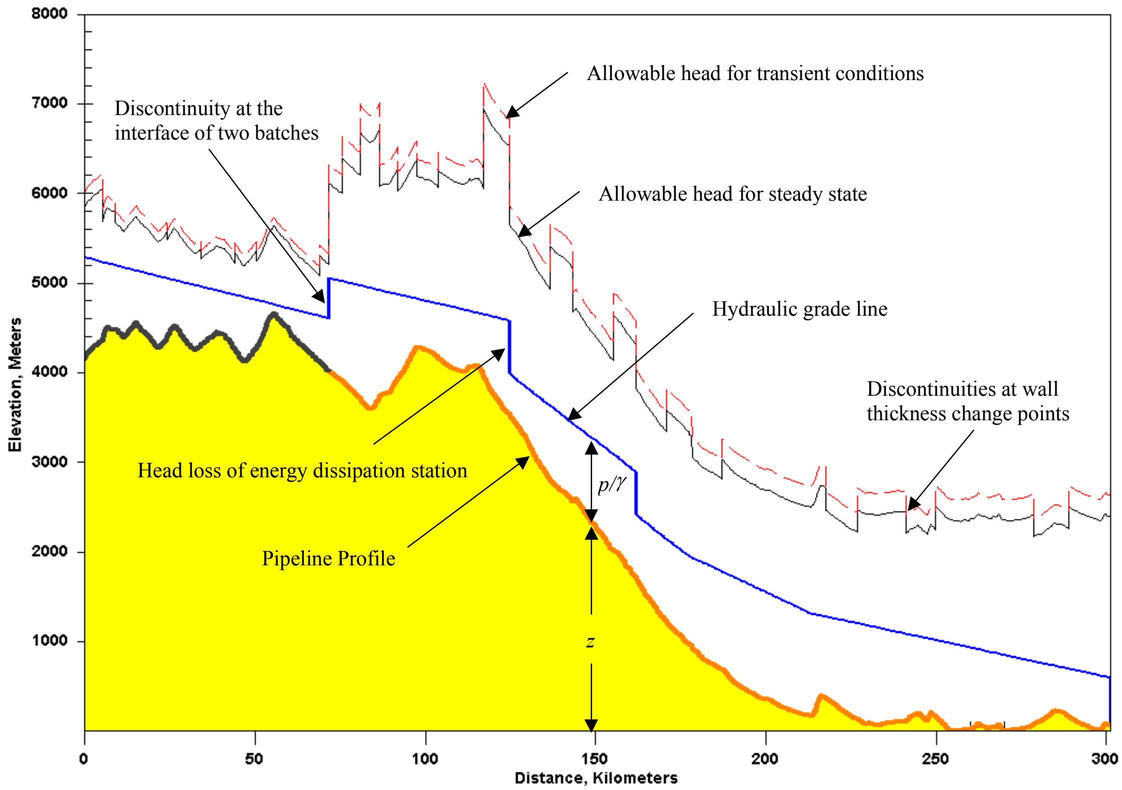

Figure 3: Definitions used in slurry pipeline engineering

4 SLACK FLOW AND BATCH HYDRAULICS

Slack flow means that the fluid transported does not fill the cross section of the pipeline. This condition occurs when the pressure in the pipeline drops to the liquid's vapor pressure, which for water is 6m to 10m, depending on altitude and water temperature. However, for practical purposes, PSI considers slack flow to occur when $p/\gamma = 0$, or when the hydraulic grade line $H = z$. Graphically, this means that we consider slack flow to occur when the hydraulic grade line intersects the profile as shown in the Figure 4.

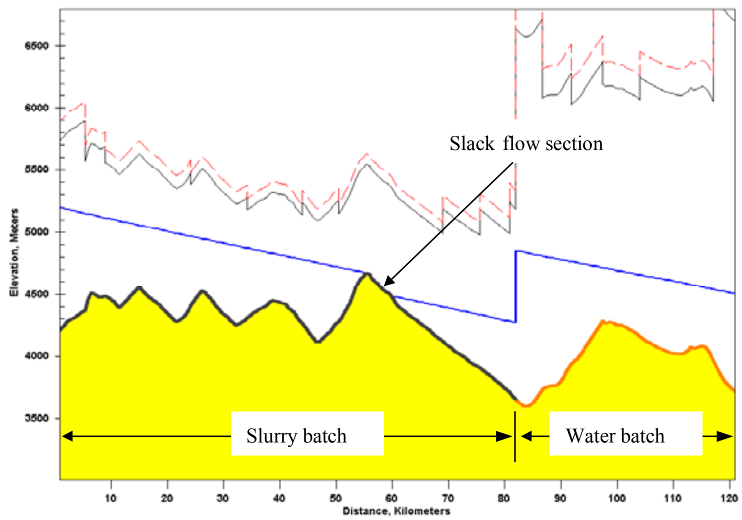

Figure 4: Representation of slack flow

Physically, when the pressure drops below the vapor pressure, we encounter an open channel flow regime, with flow velocities many times higher than for the full-pipe flow regime. In open channel conditions, the velocity (a function of the pipe diameter, the pipe grade, as well as the flow rate in the pipeline) is usually unacceptably high for slurry flow due to wear and cavitation considerations. A concentrate pipeline is expected to have a life of at least 20 years, with little to no wear when operating in a packed condition. However, when subjected to continuous slack flow, wear could erode the pipe very rapidly.

If slack flow avoidance were only a matter of maintaining the flow rate in the pipeline high enough, it would not be an issue. However, when liquids of different densities flow in a pipeline with an undulating profile, slack flow can develop when the interface of the two dissimilar liquids moves into a low point of the profile, and the denser liquid is upstream. Figures 5 and 6 show the HGL for a slurry/water batch combination at different interface locations. In both cases the flow rate is the same and the density of the slurry is assumed to be twice that of water. In Figure 5 there is no slack flow, in Figure 6, where the interface is in the valley, slack flow occurs in the slurry batch in the upstream leg of the valley.

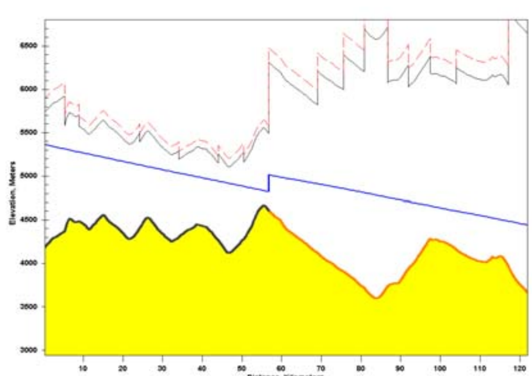

Figure 5: No slack flow

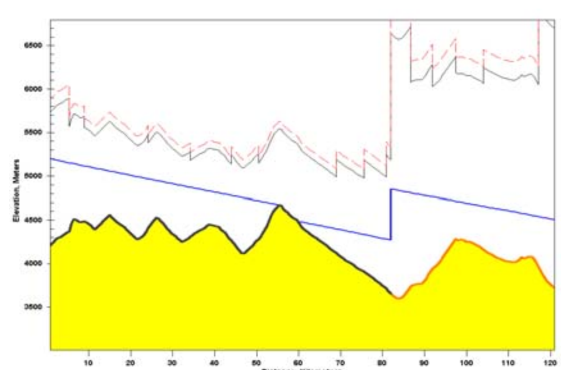

Figure 6: Slack flow occurs when slurry pushes water down

This condition presented one of the major challenges in designing a slurry pipeline to operate under batch conditions in mountainous terrain. To remedy this it was necessary to invent a device that would create back-pressure to raise the HGL and avoid slack flow. This will be discussed in the following section, entitled "Energy Dissipation."

We have shown in Figure 6, a scenario with slurry on the upstream side of the valley, and water on the downstream side, causing slack flow. However, under the same flow conditions, but with water on the upstream side of the valley and slurry on the downstream side, over-pressure occurs, as shown in Figure 8.

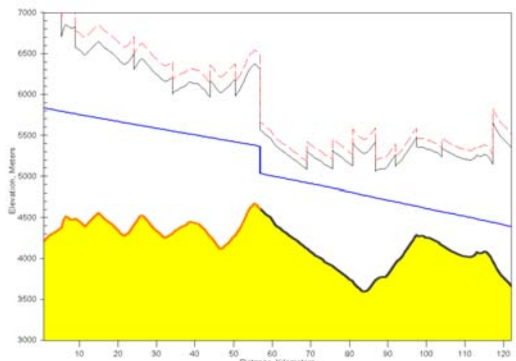

Figure 7: No over-pressure

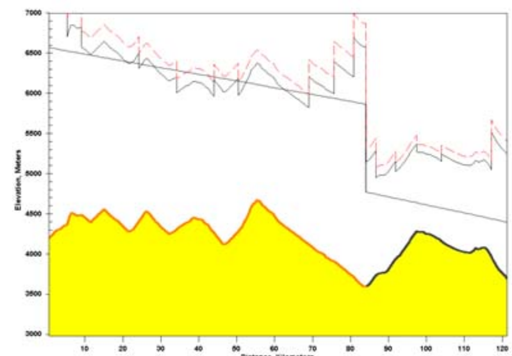

Figure 8: Over-pressure occurs when water pushes slurry down

5 ENERGY DISSIPATION

A unique characteristic of the Andean pipelines is the starting elevation. Typically, the potential energy is well in excess of that required to overcome the friction losses. Without energy dissipation devices, the excess energy would be dissipated through the formation of slack or open-channel flow, with flow velocities several multiples of packed flow. Such velocities would rapidly wear out the pipeline due to slurry abrasivity (exponential relationship).

The challenge of creating an energy dissipation device for abrasive slurry first arose during the design of the Samarco iron concentrate pipeline in Brazil. This is a 20-inch diameter, 400-km pipeline with two pump stations and one choke station. The principal device of the choke (energy dissipation) station is a ceramic orifice, as shown in Figure 9.

Figure 9: Ceramic Orifice

Chokes were first used in the Samarco pipeline in 1977, and, while the ceramics have improved and we have better designed choke holders, the basic principle remains the same. It is also necessary to polyurethane-line the pipe spools upstream and downstream of each choke due to the heavy turbulence created around the choke. Another requirement is to make the amount of choking variable, because the back-pressure is a function of the location of the water/slurry interfaces. The need to vary the amount of back-pressure applied by the chokes resulted in the design of vertical choke loops (see Figure 10). It is a simple, self-draining device, with only one valve required to engage, or disengage, a pair of chokes.

Figure 10: Choke station with vertical choke loops

All major projects in the Andes have used the same, proven technology. Ceramic technology has improved over the past two decades, resulting in prolonged parts life (six months). Figure 10 is a typical choke station used in the Antamina project. In this station there are two parallel banks of fixed chokes providing the minimum fixed back pressure, and three vertical loops for variable back-pressure. Each choke provides an average of 50-m head loss, or approximately 10 bar. On the Antamina project, a choke station provides a total head loss of up to 1,000 m of slurry, or approximately 200 bar.

6 TRAIL-OUT

In long-distance slurry pipeline operations, it is often necessary to pump water behind a slurry batch for volume control (such as in the Samarco iron concentrate slurry pipeline) or for separation of products (such as in the Antamina copper/zinc concentrate slurry pipeline). The trailing of coarse solids in the water following a slurry batch is defined as "trailout." Unlike the main slurry flow, the slurry/water interface is a dilute slurry mixing zone, which is heterogeneous and allows coarser particles to settle. The practical concerns with this phenomenon are bottom wear by the trailing coarse solids fraction, cross-contamination in a multiple product pipeline, and plugging due to rising concentration of the ensuing slurring batch (as experienced at Black Mesa coal slurry pipeline).

Solids trailout data from four commercial concentrate slurry pipelines were collected and analyzed to understand the impact of the solids trailout on the long-distance concentrate slurry pipeline engineering design and operations. The critical parameters are (1) the mixing zone length, (2) solids concentration distribution within the mixing zone, and (3) the trailing solids velocity within the flowing mixing zone.

The measured solids-water mixing zone length data from iron, copper, and zinc concentrate slurry pipelines were analyzed and compared to the available empirical correlations. The results indicate that the measured mixing zone lengths correlate well with those predicted by the traditional equal Reynold's Number methods for determining the cross contamination mixing zone length in a multiple-product transportation pipeline. [1]

In a separate paper, authored by Y. Che and R. Derammelaere, to be presented at Hydrotransport 15, the steady-state exponential distribution characteristic of solids concentration within the mixing zone is analyzed to estimate the quantity of trailed-out solids in the single product pipeline and to determine the cross contamination in the multiple-product pipeline system. The engineering design consideration to reduce the solids trailout and to minimize the cross contamination in a pipeline system transporting multiple concentrate products is also discussed in that paper.

7 TRANSIENTS

The Antamina pipeline experiences frequent hydraulic transients. Transients in the Antamina pipeline are generated by the following events:

- Pump speed change
- Power failure or pump trip
- Valve station open or close (see Figure 11)
- Choke combination change
- A different slurry or water batch passing a choke station

Computer simulations showed that the pressure caused by the transients could over-pressure the pipeline. The pipeline operators have been trained on how to control the transient pressures through operating procedures. Control interlocks are also designed into the system to prevent

[1] E.g., Interfacial Mixing of Oil Slugs in Pipelines, by Smith and Shulze.

possible accidents. Pressure relief devices are installed at the pump station and valve stations to protect the pipeline and equipment in case all preventive measures fail.

A program developed to predict transient pressures in slurry applications was developed during previous project and proven on the Antamina pipeline to give every accurate prediction. This program was incorporated into the Pipeline Simulator™, used for operator training. Using the simulator, operators can simulate shutdown conditions and observe the severity of transient pressures under varying parameters. A paper, entitled "Slurry Pipeline System: Simulation and Validation," will be presented at Hydrotransport 15 and describes the features and uses of the Pipeline Simulator™.

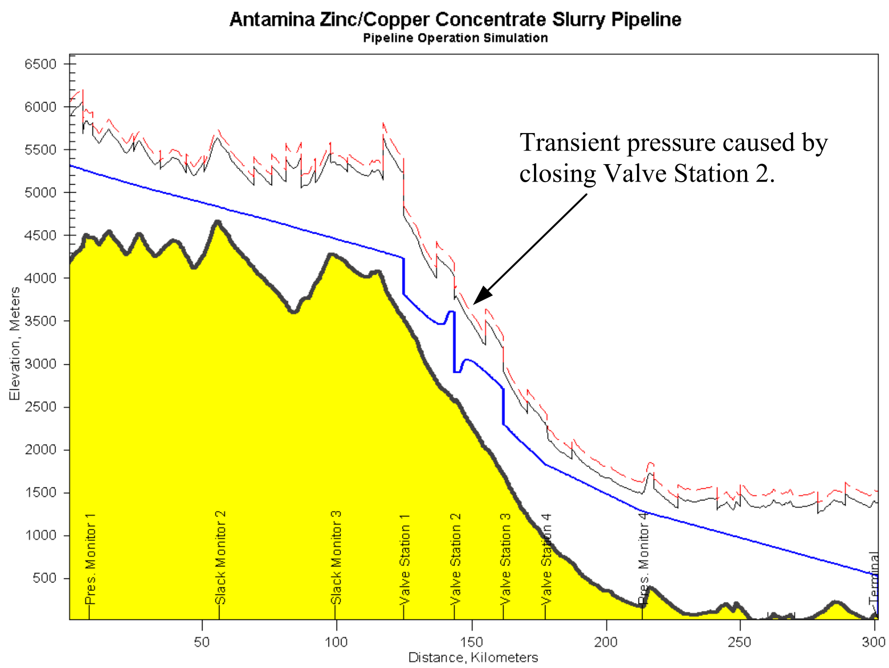

Figure 11: Transient pressure caused by closing a valve station

8 LEAK DETECTION

The leak detection system was mainly based on two methods: mass balance (MB) monitoring and section characteristic parameter (SCP) monitoring. The more reliable SCP is defined as $Q^2/(dh/dL)$, with Q representing the local flow rate and (dh/dL) representing the slope of the hydraulic gradient (headloss) in the monitoring section. The MB method alone would create false alarms when the pipeline is in transient conditions.

There are nine monitoring sections in the Antamina pipeline, separated by pressure transmitters. Based on the Darcy-Weisbach equation, the value of $Q^2/(dh/dL)$ for a specific section should be constant when the same slurry flows through it. The SCP trend for the monitoring section and its neighboring sections should move in the same direction in the absence of a leak. Leaks may occur when some lines start moving up significantly while others remain unchanged. Figures 12 and 13 show two test leaks detected by these two methods.

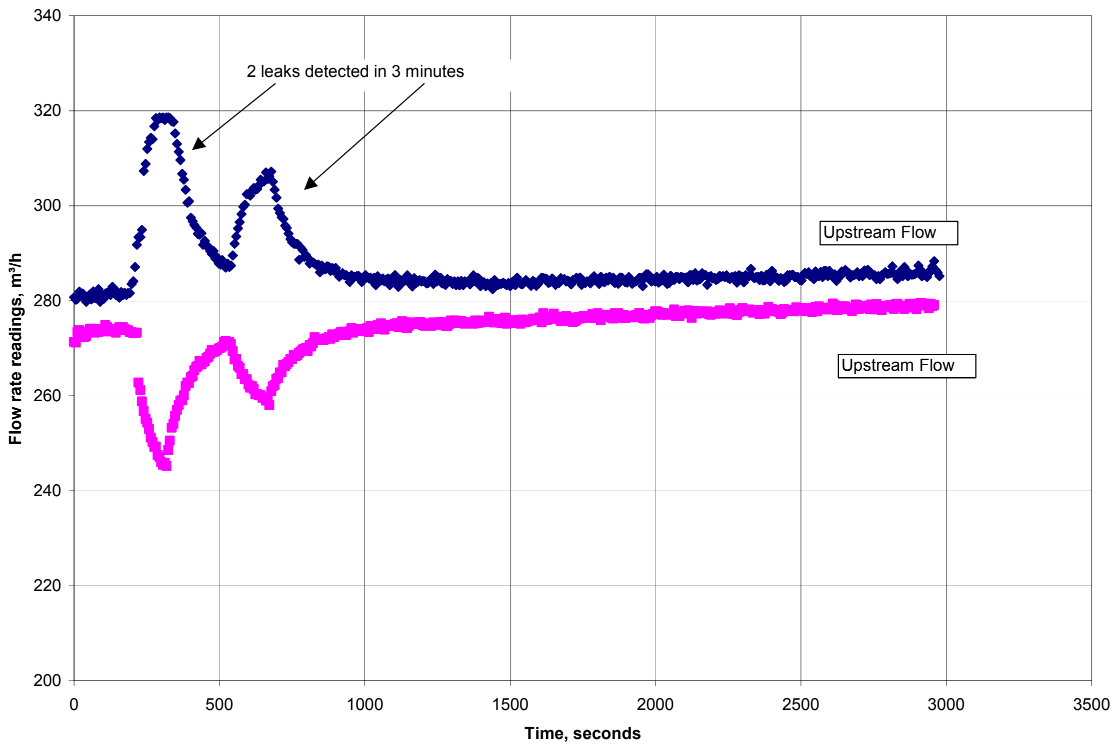

Figure 12: Leaks detected by MB method.

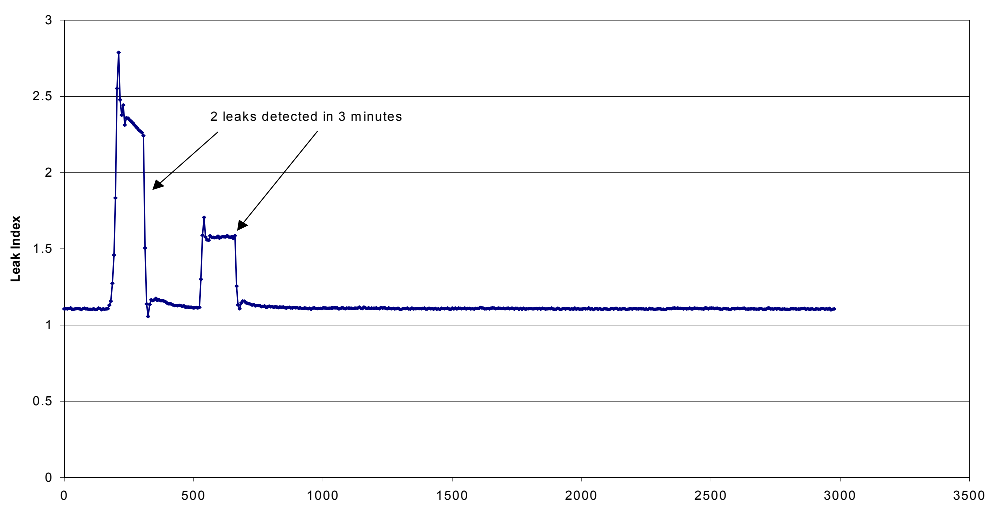

Figure 13: Leaks detected by SCP method

9 PIPELINE ADVISOR™

Pipeline Advisor™ is the pipeline monitoring software used by Antamina to conduct the complex pipeline operations. Figure 14 shows a screen of the Pipeline Advisor™. The following functions were designed into the software, and were all tested during commissioning.

- Graphical presentation of the pipeline operating status
- Over-pressure and slack-flow monitoring of the whole pipeline
- Leak detection
- Automatic batch numbering
- Batch tracking and graphical presentation on screen
- Batch arrival time forecast Expert advice to operator

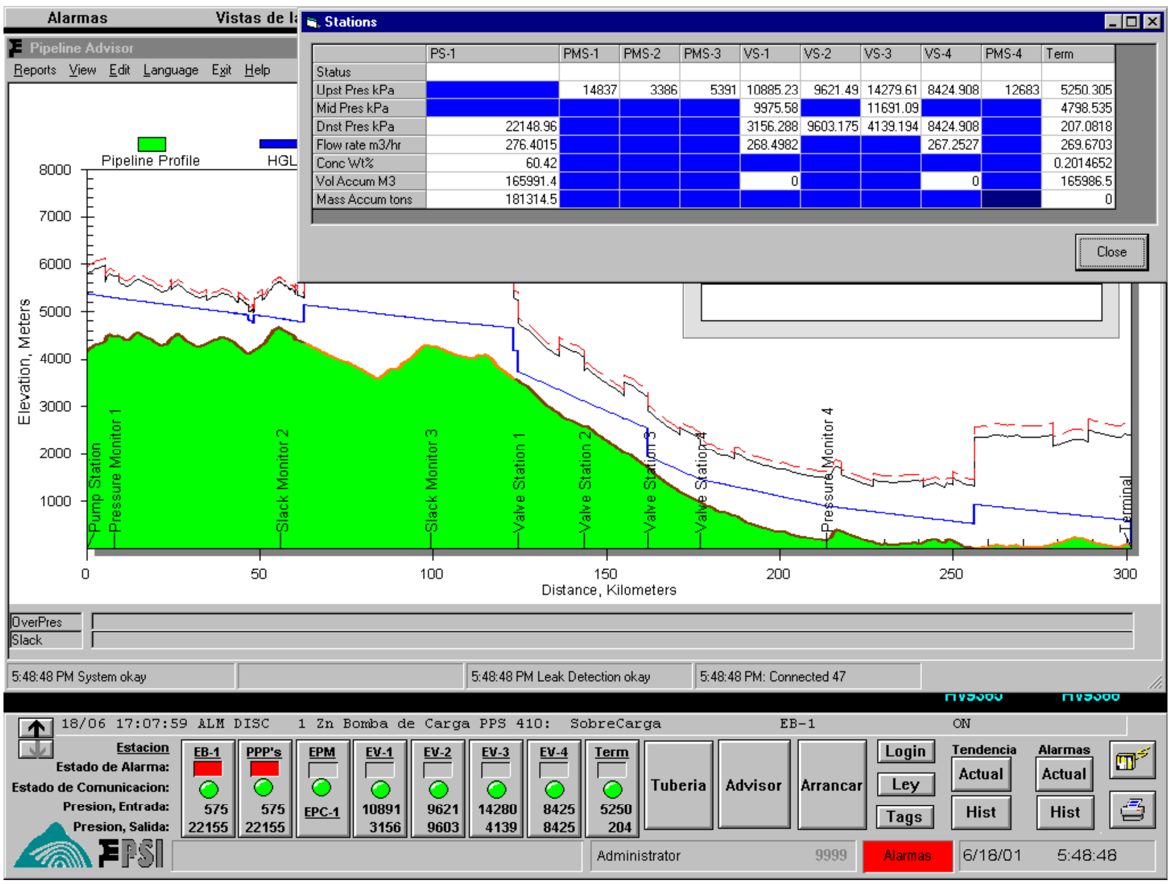

Figure 14: Screen of Pipeline Advisor™

10 CONCLUSIONS

Operating high-pressure slurry pipelines in mountainous terrain requires sophisticated designs and well-trained operators. Batching operations (intermittent slurry and water pumping) add another level of complexity. For the Antamina project, these were real concerns expressed by the owners as well as the lenders, and were carefully analyzed during the comparative evaluation of pipeline versus trucking transportation.

The Pipeline Simulator™ was in use for training of the operators more than six months prior to system commissioning, and deemed essential to prepare operators, with little-to-no knowledge of hydraulics, for one of the most complex slurry pipeline operations.

After more than six months of operations, the Antamina pipeline has proven that:

1. High-pressure slurry pumping up to 23.8 MPa is technically feasible.
2. Adjustable choke station with ceramic orifices can balance significant pressure fluctuation caused by water/slurry batches moving through rugged terrain in pipeline.
3. New technologies, such as batch tracking, leak detection, trail-out prediction, whole line pressure monitoring through Pipeline Advisor™ and sophisticated SCADA system make pipeline transportation more reliable in operation and safer to environment.
4. It is feasible to use one pipeline to transport multiple mineral products.
5. The use of the Pipeline Simulator™ is highly successful in training operators of a complex pipeline system.