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SLURRY PIPELINE DESIGN APPROACH

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Abstract:

Compared to other engineering technologies, the design of a commercial long distance Slurry Pipeline design is a relatively new engineering concept which gained more recognition in the mid 1960's. Slurry pipeline was first introduced to reduce cost in transporting coal to power generating units. Since then this technology has caught-up worldwide to transport other minerals such as limestone, copper, zinc and iron.

In South America, the use of pipeline is commonly practiced in the transport of Copper (Chile, Perú and Argentina), Iron (Chile and Brazil), Zinc (Peru) and Bauxite (Brazil). As more mining operations expand and new mine facilities are opened, the design of the long distance slurry pipeline will continuously present a commercially viable option.

The intent of this paper is to present the design process and discuss any new techniques and approach used today to ensure a better, safer and economical slurry pipeline.

1 Introduction

Slurry transport was made popular during the era of the Californian Gold Rush in mid 1800 when the "forty-niners", as the miners were then called, were panning for gold. People from all over the world flocked to California to prospect for gold. With so much people mining, some miners realized that to increase their chances of finding gold they have to accelerate the panning process. Some creative miner considered simulating the river flow condition in a sluice to separate gold from soil by mixing with water and thus increased their chances of finding more gold from the rest of the miners. The sluice were later lengthened and adjusted to direct the processed soil to a damp site and allow more access to unprocessed soil. This method is still commonly used in some mines today in slurry tailings transport.

It was not until the 1960's when the commercial viability of long distance pipeline was recognized. Currently, there are scores of commercially operating long distance slurry pipeline worldwide. The need to transport slurry through pipeline is ever increasing as demand for metal products throughout the world increases.

The intent of this technical paper is to present in the most practical layman's terms, the considerations, the design processes and the impact of new technologies to current slurry pipeline design. The targeted audience includes both the non-technical persons who are involved in the mining business and mining technical persons but whose specialty is on other processes.

2 Slurry pipeline systems

At present, the mining industries, commonly utilizes slurry pipeline in the transport of mineral ore, concentrate or tailings. In the transport of concentrate, a typical system will include an agitated storage feed tank, a pumping station, the pipeline and a receiving terminal. In some cases, a valve station and pressure monitoring station is included for improve pipeline operation (see Figure 1).

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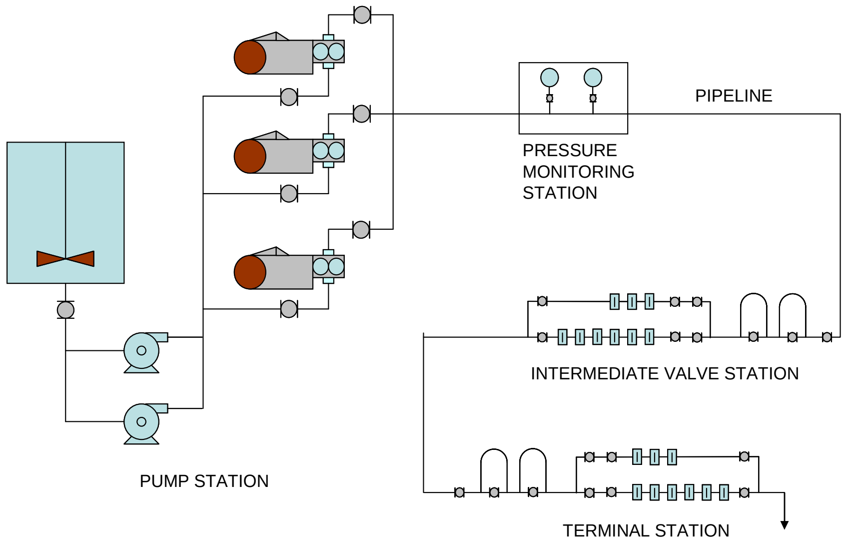
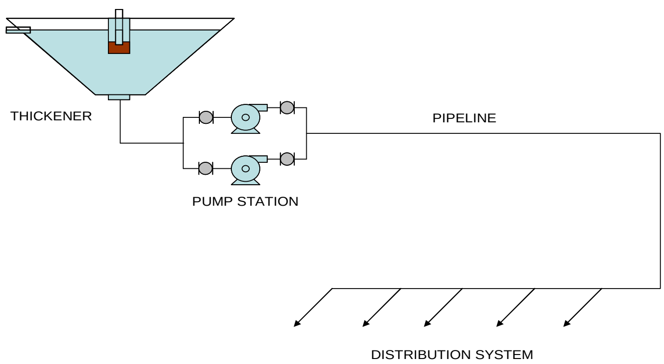


Figure1. Typical Diagram for a Concentrate Pipeline System with Positive Displacement Pumps.

In the transport of mineral ore or tailings, a typical system could be either by open channel or by full flow pipeline. A full flow pipeline system will typically include a Centrifugal Pump, a pipeline and a delivery system at the disposal site (see Figure 2). An open channel, which flows by gravity, will include a feed well, a sluice channel and a delivery system to the disposal site. In most cases, this system will include a launder or an energy dissipating drop boxes along



the delivery route (see Figure 3).

Figure 2. Typical Diagram for a Tailings Pipeline System with centrifugal pumps.

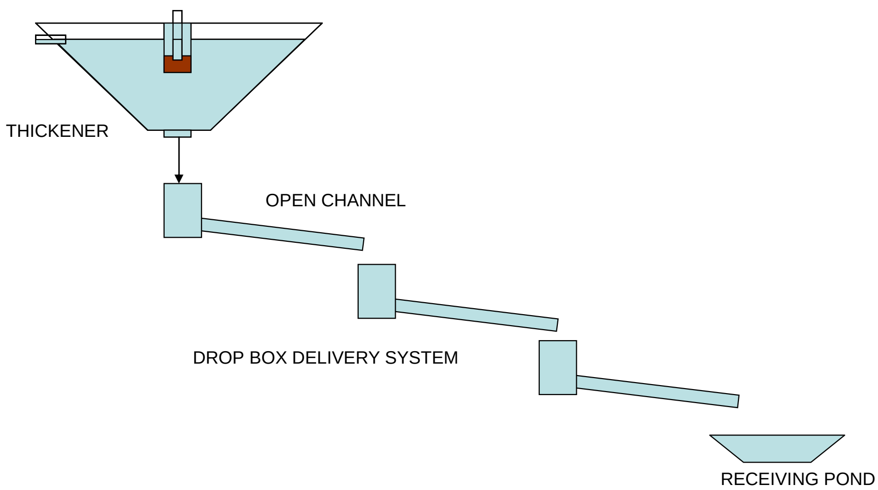


Figure 3. Typical Diagram for Open Channel Tailings System

3 Design considerations

To determine the most economical pipeline system to use, it is important to consider the location of facilities, pipeline route, characteristics of slurry and amount of solids (throughput) to transport. The combination of these parameters defines the economic viability of the pipeline transport system. In view of these, each parameter will be discussed briefly to understand its impact for a safe and economic pipeline design.

3.1 Facility Location

This refers to the location of the mine plant facility where the pipeline begins and ends at the receiving terminal which could be a dam or a filter plant. The relative location between these two facilities will dictate the hydraulic head required for the transport system. In most cases, the selection of the location of these facilities is driven by political, economic and/or environmental needs.

3.2 Pipeline Route

This is the most important aspect of the pipeline transport design which could define the beginnings or end of the project. Theoretically, the most economic route would be one with a continuous 1% downgrade and traverses the most direct route as possible with no intermediate high points (see Figure 4). This, however, is hardly seen in practice. Therefore, it is the objective of the designer to select a route that closely assimilates the theoretical condition. The pipeline route selection will require the expertise of both the hydraulic engineer geotechnical specialist and the construction specialist. For slurry pipeline, it is the concern of the hydraulic engineer to find the shortest route (lower pressure losses), the least slope (for ease in operation and maintenance) and one with most consistent elevation (for low pumping head). The geotechnical specialist identifies possible construction difficulties such as rock formations, river crossings, landslides, seismic faults and other geological formations that could affect pipeline route. It is the intent of the construction specialist to evaluate ease of constructability through the selected route.

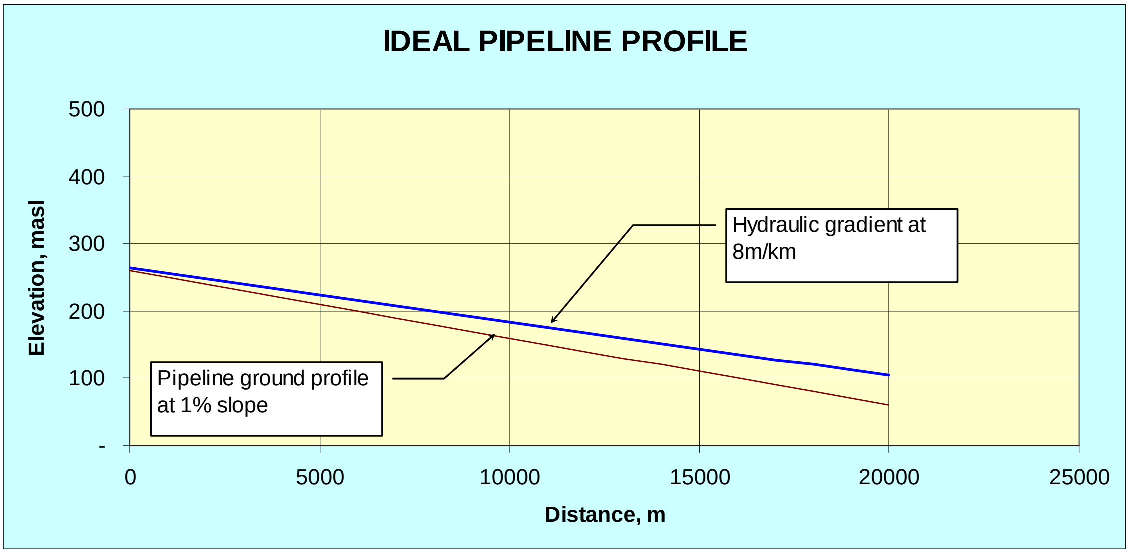


Figure 4. Ideal Pipeline Ground Profile with 1% Slope.

3.3 Slurry Characteristics

The transport of slurry is nowhere close comparable to transport of water as some people envision. The mixture of solids and liquid produces an entirely different solution with has its own rheological and fluid properties. The inability to fully appreciate the flow behavior of slurry could cause serious pipeline failure that could lead to violation of environmental laws, equipment failure or loss of life.

Slurry characteristics definition can be performed in 2 phases. The first phase is by laboratory testing where a representative sample of the slurry is prepared at different concentrations. From this test, the slurry particle size distribution and rheology are obtained (see Figure 5). The result of this test is sufficient to produce an engineering document for the Pre-feasibility Engineering level.

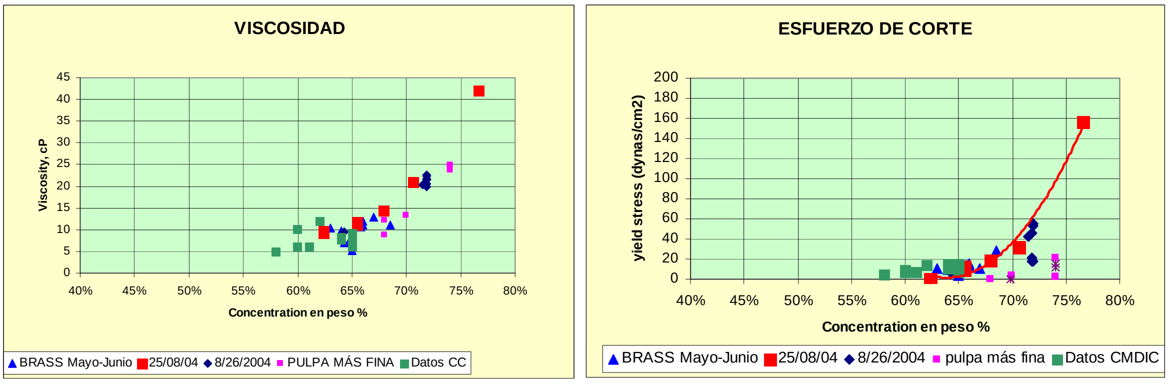


Figure 5. Typical Viscosity and Yield Stress Charts

Should the project proceed, it is recommended to do the second phase, which include test loop testing to confirm lab test results and calculated pressure losses. The result of this test should aid in narrowing down the project capital cost estimate to +/- 10% accuracy during Feasibility Engineering level.

3.4 Throughput Capacity

The other issue impacting the pipeline design is its design throughput. If the throughput is very low (less than 700,000 dry Tons per year), the pipeline diameter will be in the order of 6" or smaller. Under this condition the cost of slurry (in tones) transported per km of the long distance pipeline installed can increase beyond attractive investment cost levels. In this case, justification for a small diameter pipe would largely depend on accessibility and environmental issues.

4 Design approach

4.1 Slurry Minimum Velocity Calculation

Based on the lab test results as discussed in Section 3.3 above, hydraulic calculations are made to determine the minimum velocity and the friction losses of the pipeline. The minimum velocity is determined by identifying both deposition velocity and the transition velocity. The pipeline minimum transport velocity is the higher of the two values for a given solids concentration.

Turbulent flow must be maintained where solids exhibits settling tendency[1].

Given slurry characteristics and pipe diameter, a plasticity number (also named Bingham number), which is a ratio between intrinsic fluid, flow and geometry shear rate scale, is then calculated. The critical Reynolds number (a balance between inertial and viscous forces) is then determined and the corresponding transition velocity is identified. One of the most common correlations used for this calculation is one by Hanks and Ricks[2].

For concentrate pipeline systems, operating in the turbulent regime prevents solid settling by the action of turbulent mixing. This calculation requires re-iteration and is best executed using computer programming. For non-settling solids, which is usually associated with homogeneous mixtures such as thickened tailings, sewage sludge, mayonnaise, toothpaste, etc., laminar flow may be considered.

Deposition velocity is associated with heterogeneous flow where a gradient exists in the distribution of solid particles across the cross section of the pipeline. These slurries involve fast settling solids (coarse particles) that would require turbulent flow for re-suspension. There are however some coarse particles that turbulence alone may not be sufficient to keep in suspension. These particles travel along the bottom of the pipeline in continuous jumps and rolls motion known as saltation. The basic equation used for determining deposition velocity on uniform solids is based on the Durand[3] correlation.

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[1] Slurry and Sludge Piping by Ramesh Ghandi, Piping Handbook compiled by M. Nayyar, p. C.455-C.499, 6th Edition.

[2] Hanks, R. W. and Ricks, B.L. , Laminar-Turbulent Transition in Flow of Pseudoplastic Fluids with Yield Stress, J. Hydronautics, Vol. 8, No. 4, pp 163-166 (Oct 1974).

[3] Durand, R., The Hydraulic Transportation of Coal and Other Materials in Pipes, Colloq. Of National Coal Board, London (Nov 1952).

$$V_d = F_L \left\{ 2gD_i \left[\frac{\rho_s - \rho_L}{\rho_L} \right] \right\}^{\frac{1}{2}}$$

Where:

F_L = Durand factor based on Cv and d50
Di = Inner diameter of pipe (in m)
g = gravity acceleration vector magnitude (9.81 m/s)
ρ_s = solids density mixture (kg/m3)
ρ_L = Liquid density (kg/m3)

From this equation, numerous modifications were made including considerations for non-uniform solids. Among those are by Zandi and Govatos, Wasp and McElvin-Kave (or known as modified Durand). Subsequently, these equations have further evolved and carried as company secrets which are optimized based on correlations to actual operating conditions.

Operating the pipeline at or below the deposition velocity for a prolonged duration can cause eventual pipeline blockage. Figure 6, shows a typical diagram representing the results of the deposition and transition velocity calculation as plotted versus solids concentration by weight.

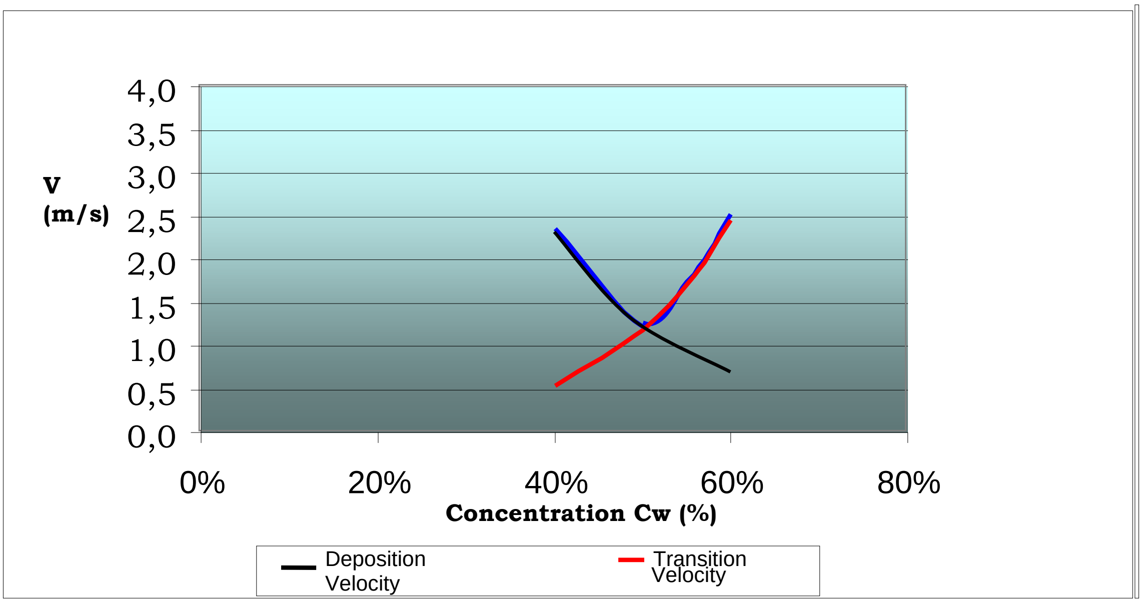

Figure 6. Typical transition and deposition velocity curves. The blue line represents the maximum value between the deposition velocity and transition velocity.

4.2 Friction Loss Calculation

For slurry in Homogeneous flow, the most common equation used for determining friction loss is by the use of Darcy's equation which is modified to adopt for Newtonian slurry. For homogeneous flow in turbulent regime, the friction factor is determined using Colebrook's equation:

$$\frac{1}{\sqrt{f}} = 4\log\left(\frac{Di}{2\varepsilon}\right) + 3.48 - 4\log\left(1 + \frac{9.35Di}{2\varepsilon Re\sqrt{f}}\right)$$

where:
Re = Reynolds number, defined as $Re = \rho V D_i / \eta$, with ρ the density of the slurry, V the mean pipeline velocity and η its dynamic viscosity.
ε = absolute roughness (same unit as Diameter)
f = Fanning friction factor

The friction loss is calculated using Darcy's equation, as follows:

$$\frac{h}{L} = \frac{f \times V^2}{2 \times Di \times g}$$

where:

h = Friction head loss between 2 stations (m)
L = Distance between 2 stations (m)
f = Fanning friction factor (dimensionless)
V = mean pipeline velocity between 2 stations (m/s)

For slurry in Heterogeneous flow, the determination of the friction loss is more complex. The most common method is the one proposed by Wasp[4], which is an iterative procedure as follows:

1. Divide the total size fraction into Heterogeneous and Homogeneous part.
2. Compute the friction loss for the homogeneous part using the rheological properties of slurry. Calculate the friction loss of the heterogeneous part using Durand's formula. The sum of the two parts gives the initial estimate of the slurry friction loss.
3. Determine the ratio of the volume fraction of solids C/C_A (fraction of solids 0.98D from the pipe bottom to fraction of solids to pipe axis) for each size fraction based on the value of the friction loss determined in step 2.
4. Based on these new values of C/C_A, determine the fraction of solids in the homogeneous and heterogeneous phases.
5. Re-compute the friction loss of the slurry for step 2. This iteration process continuous until the new estimate closely agrees with the previous estimate. This method is better performed using computer programs.

4.3 Steady State Hydraulic Calculation

Having determined key parameters indicated in Section 3, pipeline design may commence by developing a Steady State calculation. This is basically a hydraulic calculation based on Bernoulli's equation to determine required system head performed using a simple programming language or with a spreadsheet.
Bernoulli equation:

$$(Ep + Ev + Ez)_1 + E_A = (Ep + Ev + Ez)_2 + E_E + Ef + Em$$

$$\frac{P_1}{\rho} + \frac{U_1^2}{2} + Z_1 g + E_d = \frac{P_2}{\rho} + \frac{U_2^2}{2} + Z_2 g + E_E + E_f + E_m$$

where subscript 1 and 2 refers to points 1 and 2, respectively.

$Ep = P_1/\rho$ = Pressure at point 1 divided by slurry density, m
U^2 = Kinetic head (velocity), m
Z_1 = Static head at point 1, m
$E_A = E_d$ = Pump head, m
E_E = Extracted energy (ie. Turbine), m
Ef = Pipeline friction losses, m
Em = Minor losses (valves, fittings, etc.), m

It is recommended that during this process a sensitivity analysis should be made between pumping cost and pipe material cost by varying pipe diameter. In slurry pipeline design, care must be taken such that the minimum operating line velocities is greater than slurry deposition velocity and at the same time maintain turbulent flow.
The Steady State calculation, determines the initial values to use for the pipeline diameter, pipe wall thickness, required pumping head, the amount of intermediate valve stations and the amount of choking (energy dissipation) required.

4.4 Transient Hydraulic Calculation

The Transient Calculation is required to ensure that the selected pipe wall thickness selected during Steady State calculation is sufficient. Transient pressure is created whenever there is a sudden operational change in the pipeline, such as pump start up, pump shutdown, valve closure, or chokes changes. The induced pressure wave propagates from the source of pressure disruption. Since this presents a dynamic motion, this calculation is best appreciated with graphical presentation using computer models (see Figure 7).

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[4] Wasp, E.J., Kenney, J.P., and Gandhi, R.L., Solid Liquid Slurry Flow Pipeline Transportation, Trans Tech Publications (1977)

Figure 7. Sample of a Transient Dynamic Model.

5 Application of new technologies

This Section discusses how new emerging technologies has helped in the design and safe operation of the pipeline. Some of the noted emerging technologies are as follows:

5.1 Global Positioning System (GPS)

The GPS is a functional Global Navigation Satellite system. Utilizing a constellation of at least 24 medium Earth orbit satellites that transmits precise microwave signals that enable the receiver its location, speed/direction and time with very good accuracy. This system was developed by the United States Department of Defense and is managed by the United States Air Force, 50th Space Wing. The cost of maintaining the system is approximately US$ 750 million per year.

The design of the pipeline system has been benefited by this technology in helping locate pipeline routes with more efficiency and speed. Where it used to take weeks in walk down route survey and enormous cost for aerial surveys, this activity could be performed with more precision and speed through computer systems. It still however takes to manually stake the ground to identify pipeline centerline and corridors.

5.2 Leak Detection System (LDS)

The Leak Detection System is a computer model that detects the location and size of a pipeline leak, This model is similar to an instrument that aids in the providing information on actual field conditions. As such, it needs periodic calibration to ensure accuracy.

Commercially available computerized leak detection system utilizes either one or a combination of the following methods:

- Volume Balance
- Pressure Point Analysis
- Transient Model Methods

Since Liquid and Slurry pipelines transport a “non-compressible” fluid, transient pressure wave speeds are relatively fast and therefore system reaction times are short. This translates into relatively rapid leak detection and location determination. The momentum and continuity equations are utilized to calculate system responses to stimuli in terms of time and distance along the pipeline.

The “Volume Balance” method attempts to balance what has flowed into the pipeline with what has come out. It is a “book-keeping” or “accounting” type calculation on flow and/or mass rates. Since a pipeline almost never is in a true “steady-state” condition, the balance has to be integrated over long time periods (in terms of hours) in order to avoid false signals. Therefore, this method has a weakness as a leak can not be allowed to continue for long periods of time.

The “Pressure Point Analysis” is a statistical method which compares pressures changes along the pipeline to determine abnormal behavior based upon a steady state assumptions. However, this method is defective by itself if strong transients are traveling along the pipeline because it can not differentiate between transients induced via a leak (or plug) or by changes in equipment status along the system. This method can accurately determine leak location in terms of minutes, but only when system equipment status remains constant.

The “Transient Model” method compares calculated system pressures based on actual operating pipeline condition and is compared with those measured. It can be installed as a standalone computer connected to the DCS/SCADA system, but could be incorporated into the DCS/SCADA programming. This method is effective as it can track operating variables even as equipment status changes are effected in the system. Also, detection periods are reduced to seconds and minutes depending upon the distance of the leak from sensors and its magnitude.

There are other leak detection methods that use sonic signatures, conductivity, or other physical contact techniques but have been found ineffective for slurry pipeline application, especially when long distances are involved.

A properly managed Leak Detection System helps pipeline operation in determining occurrence of leaks and thus helps provide faster response in leak containment and mitigation.

5.3 Expert Control Systems

The Expert Control System is a computer based model that interacts with the DCS of the mine plant. It takes input data from the pipeline operating faculties through the DCS and performs a set of logical algorithms. An output is generated to control the pump operation and/or the engagement of valve station chokes to optimize operating conditions. At the present high cost of energy, this technology could lead to considerable economic savings to mine plant operation.

5.4 On line Viscometer

Due to the high cost of energy, the operation of the slurry pipeline has become an important cost factor for operations. The use of an on-line viscometer for slurry applications, help in establishing efficient pumping operations through optimization of slurry concentration. The instrument is usually installed parallel to normal process flow. On-line rheology measurement includes determination of apparent viscosity and yield stress.

5.5 On-Line Corrosion-Erosion Monitoring System

The need for an on-line corrosion-erosion monitoring is more important than ever due to more stringent safety and environmental standards. The installation of an on-line corrosion-erosion monitoring system is specially appropriate for unlined pipes used for water and tailings transport. This technology basically utilizes an electrical resistance probe with on-line monitoring. Manufacturers may differ in probe type and the methodology of insertion. It may be made of round wires, bars, small pipes or flange probes that are exposed in the flow path inside the pipeline. A wear of the probe would indicate a change in the electrical resistance that would indicate the amount of wear. The probes are inserted at pre-determined intervals along the length of the pipeline with the indications transmitted remotely by radio or fiber optic cables to SCADA system.

4. Other recent developments affecting pipeline design

In Chile, the following factors water availability, energy supply and environmental laws have recently played an important role for the design of slurry pipelines. These factors have radically changed mining concepts since they could no longer be taken for granted during the design phase.

Water use issue has affected most of the Chilean mines as the “Dirección General de Aguas (DGA)” has started restricting desert water (salt water beds) usage. In the past, tailings are commonly transported at low solids concentration (20% to 30%) requiring high water usage. Due to the imposed water restrictions, thickened tailings (high solids concentration) have become an attractive option. For this reason, mining operators have started exploring seawater desalination plants and thickened tailings part of the mining process system. Some mines have even considered directly using sea water for process water.

In recent months, supply of energy has also been curtailed due to shortages in the supply of natural gas. This development has caused some mining companies to develop their own power generating units considering different sources of fuel such as coal and geothermal.

Local agricultural communities are becoming more aware of their water rights and have become more vocal in presenting their case to the local government. These concerns include protection of the local fauna and flora that may be affected by the mine development. These cases have been presented so strongly so as to affect the mining plan some companies within the North Chilean Region.

5. References

PIPING HANDBOOK, Mohinder L. Nayyar, PE, Seventh edition-Mc Graw - Hill Handbooks