Long-distance slurry pipeline transport*

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Abstract

This chapter of the *SME Surface Mining Handbook* deals with long-distance slurry pipelines, defined as those longer than 10 km is used to transport solid materials, including ore, concentrate, and tailings, mixed with water, where the latter acts as a medium. Such pipelines tend to pass through public and private sites, and commonly through natural topographies and barriers that require the construction of numerous ascending and descending sections. This type of transportation mode is an alternative to other traditional means of transport such as trains, trucks, and conveyors. The chapter covers a variety of topics related to slurry pipelines, including their advantages and disadvantages, slurry properties, hydraulics, infrastructure, commissioning and operation, and pipeline integrity.

Keywords: Long distance pipelines, Bingham fluid, pipeline integrity, pressure losses

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1. Introduction

This chapter deals with long-distance slurry pipelines, herein defined as those longer than 10 km and being employed to transport solid materials including ore, concentrate, and/or tailings, mixed with water, where the latter acts as the medium. Such pipelines tend to pass through public and private sites, and commonly through natural topographies and barriers that require the construction of numerous ascending and descending sections. This type of transportation mode is an alternative to other traditional means of transport such as trains, trucks, and conveyors. Figure 1 on the following page shows a typical view of an installation of a long-distance transportation system for mining, prior to the pipes being welded and buried.

Following some applications in hydraulic coal transportation during the 1950s, the earliest systems for transporting limestone and iron ore by pipelines over long distances date back to the 1960s. The 1970s was very prolific both in the construction of new transport systems, including copper concentrate and tailings, and in the development of new knowledge, driven in part by the launching of numerous new conferences and trade events specialized in this technology. While the short-distance transport of mined materials can be used for either the hydraulic transport (or pretreatment) of slurries, long-distance slurry pipelines are currently only used in the mining sector for transportation purposes. Typical slurries are nickel, phosphate, bauxite, and kaolin concentrate, among other solid suspensions, and they are transported over distances that can be in excess of 500 km and in capacities of greater than $70\,000\,\mathrm{t\,d^{-1}}$ (metric tons per day) of solids. A number of long-distance pipelines

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Figure 1: A long-distance slurry pipeline during its construction phase

relevant to the mining industry are referred to by Jacobs (1991), Abulnaga (2002), and, more recently, Ihle (2020).

This chapter presents a brief description of the most important aspects of long-distance pipeline transportation systems in mining. This description is not exhaustive, and some aspects of related design and operation have been omitted, thus allowing a focus on the concepts that are unique to this kind of infrastructure. In particular, the description of calculation details has only been made to clarify concepts, and thus formulas and derivations oriented to specific calculations have been omitted. However, this chapter includes both references and suggested further reading as a complement to those wishing to delve deeper into the subject.

2. Comparison with other transport methods

There are four major alternative methods of solid transport over long distances: trucking, railways, conveyor belts, and slurry pipelines. While conveyor belts have been included in this list, they are primarily used for handling bulky materials (such as raw ores) within mining areas and are not applicable for long-distance transport (*i.e.*, $> 10\,\mathrm{km}$).

Compared to trucking and railway, pipelines have proved to be an economical and environmentally friendly method for transporting different types of large-tonnage minerals of over long distances. Their advantages and disadvantages are discussed in the following sections.

2.1. Advantages

Like most engineering procedures, long-distance transport by pipeline has numerous well documented advantages:

- Pipelines have high availability and can operate continuously if the upstream production is not interrupted. While pressure and density are critical, most design considerations are such that the operation is not affected by weather conditions (except extreme cold, when the pipelines have not been buried below the frost layer). Most mineral concentrates require a beneficiation process that involves grinding the ore to a very fine size to achieve good beneficiation. This is a wet-method process and the particle size distribution of the concentrate products or tailings renders them suitable for long-distance pipeline transportation. If the pipeline is properly sized (based on the throughput of the beneficiation plant) and the slurry has the correct characteristics, the settling of solids in the pipeline can be avoided.

- There is less loss of material compared to trucking or railway transport.
- Pipelines can follow a more direct route (compared to railways or roads) because higher slopes can be negotiated. Hence, transport distances can be reduced considerably.
- Slurry pipelines are normally buried underground, and therefore do not interfere with surface traffic and population. In some cases, this also implies there is less risk of transport interruption due to road links being cut or from theft of concentrate.
- Pipelines do not produce a noise or dust problem, as is frequently the case with trucking or railway transport.
- The pipeline right-of-way can be restored to its original condition after the line has been constructed (and buried, if required).
- The risk of slurry leaks or spills is very low, and a leak detection system can be installed to allow early warning of such instances, thereby reducing both potential environmental damage and product loss.
- Once installed, pipelines require less labor to operate than other transport infrastructure and therefore are comparatively less prone to labor-related disruptions and problems.

In oil sands usage, hydrotransport (relatively short distance in contrast to the major usage already mentioned in this chapter) allows a preconditioning of the mined materials prior to their input into the extraction process. Hydrocarbon extraction from oil sands relies on hydrocyclones to separate the bitumen solids, with warm water and caustic soda being the traditional ingredients/reagents, so (despite the short distances) it makes sense to incorporate a hydro-transport aspect of conventional surface handling methodologies. It also reduces the number of hydrocyclones and their retention time because the conditioning has already been achieved in the pipe during its (short) transportation. Having said that, an economic trade-off study should still be made between the pipeline transport and other traditional methods if the transport distance is short (*i.e.*, less than 10 km). For long-distance pipelines, the unit transportation costs are generally low, and the costs decrease with an increase in the slurry solids tonnage or transport distance.

2.2. Disadvantages

And conversely, long-distance transport by pipe has the following disadvantages:

- Long-distance pipelines are a fixed asset/system and therefore there is little or no flexibility, and as such they are incapable of coping with variability in any of the components (such as product, medium, or location).
- Long-distance slurry pipelines require proper control of particle size, as well as slurry concentrations and rheology, to ensure reliable and trouble-free operation.

- A significant amount of water is required for slurry preparation.
- The pipelines have lower flexibility of throughput compared to trucking or railway transport, so if the throughput falls below a certain level, they are difficult to maintain (although "batching" can overcome this situation).
- The initial investment for pipeline transport is usually higher compared to that for trucking or railway transport (if the train line is already in existence).
- After the pipelines have been installed, they cannot be rerouted without interrupting production of the whole system.
- Right-of-ways are required to enable proper maintenance.

3. Slurry properties

Pipelines are used to transport a wealth of bulk materials, ranging from fuels to ores and tailings. Examples are coal slurries, which were among the first applications of this technology. Other common slurries transported by pipeline are limestone, iron ore and tailings, phosphate, copper concentrates and tailings, bauxite, oil sands (both the ore and the tailings), and uranium tailings. However, the common requirement for successful transport in pipelines is having the correct slurry characteristic.

3.1. Slurry characteristics

Better suited for long-distance pipeline transport are those materials with relatively fine particle size distribution, so there is not such a strong energetic requirement associated with resuspension. Figure 2 shows examples of density ranges and the particular case of particle size distribution of a typical copper sulfide tailing (denoted as "whole tailing"), with two streams resulting from passing through a hydrocyclone, namely, the overflow, corresponding to slimes (*i.e.*, fine content) and sand (coarse fraction) denoting the whole tailing, slime (fine content), and sand (coarse fraction) (Figure 2a). An additional example of particle size distribution of a copper concentrate can be found in Ihle et al. (2013), where values of d_{50} and P_{80} 28.6 µm and 94.4 µm, respectively, have been reported.

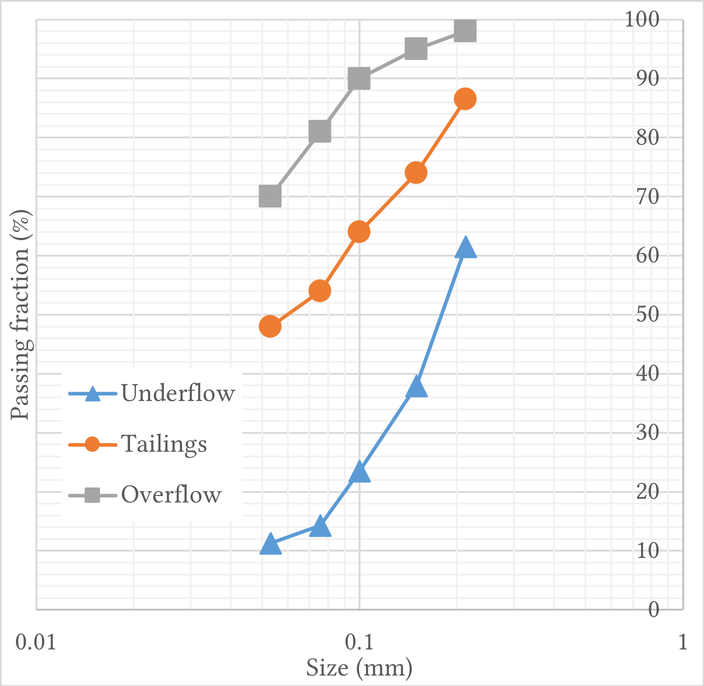
Depending on the specific gravity of solids, typical solid volume concentrations (C_V) related to turbulent transport are between 28 % and 30 %. Here, C_V is the solid volume fraction, defined as $Q_p/(Q_p + Q_f)$, where Q_p and Q_f, denote volume flow of the solid and fluid phase, respectively (also, $Q_p + Q_f = Q$, with Q being the slurry bulk volume flow). Operators of long-distance pipelines often use solid fraction by weight (C_p) instead of the volume fraction as a control parameter. These can be described as

$$C_V = \frac{C_p}{C_p + S(1 - C_p)} \tag{1}$$

where $S = \rho_p/\rho_f$ and is the specific gravity of solids, with ρ_p and ρ_f, respectively, being the solid and fluid phase densities. Thus, depending on whether the slurry is tailings or concentrate, the corresponding valuable mineral C_p can typically range between 50 % and 70 %.

3.2. Slurry rheology

The energetic consumption associated with hydraulic transport of slurries and their flow characteristics may depend strongly on their rheology. According to the definition from the Society of Rheology, rheology is *the science of deformation and flow of matter* (SOR, 2022). Although slurries are not fluids *per se*, they are often assumed to be if they can be treated as a homogeneous mixture.



(a) Typical copper tailing upstream (whole tailing) at the overflow and underflow of hydrocyclone

Slurry type	S	pH
Iron concentrate	4.5–5.2	6.0–11.0
Copper concentrate	4.1–4.8	9.5–11.5
Zinc concentrate	4.0–4.5	5.0–10.0
Nickel laterite	3.0–4.0	6.0–10.0
Bauxite	2.5–3.0	8.0–12.0
Iron tailing	2.5–3.0	7.0–9.0
Copper tailings	2.5–3.0	8.0–11.0

(b) An overview of typical specific gravity and pH ranges of mining slurries

Figure 2: Slurry characteristics

When phase separation occurs, for example, when gravity causes segregating into a denser slurry and a pure liquid phase, the rheological assumption is no longer valid. Assuming a homogeneous condition, rheological characterization relies on the assumption that there is relationship between a shear stress applied to the fluid (tangential force per unit area, τ) and its response via a shear rate ($\dot{\gamma}$), which corresponds to the gradient of the velocity

$$\tau = f(\dot{\gamma}) \tag{2}$$

In the simplest case of a Newtonian fluid, $f = \mu\dot{\gamma}$ and the proportionality constant, μ, corresponds to the dynamic viscosity. The equality between the velocity gradient and $\dot{\gamma}$ can be readily seen, noting that in an infinitesimal vertical distance $\mathrm{d}y$, associated to horizontal displacement $\mathrm{d}x = [u(y+\mathrm{d}y) - u(y)]\mathrm{d}t = \partial u/\partial y \mathrm{d}t$, it follows that $\tan(\mathrm{d}y) = \mathrm{d}y = \mathrm{d}x/\mathrm{d}y$. A schematic of this construction is depicted in Figure 3 on the next page.

Although at high concentrations and under the presence of certain reagents (such as flocculants), the slurry of interest can exhibit time-dependent behavior, especially progressive thinning under constant shear rates over time (Nguyen and Boger, 1985, 1998), at mid to low concentrations such effects are of second-order importance. Figure 4 on the following page shows a schematic of the most common time-independent rheology models used in the context of long-distance pipeline transport.

The various curves in Figure 4 on the next page can be expressed succinctly in analytic form by the following conditions:

$$\dot{\gamma} = 0 \text{ if } \tau < \tau_y \tag{3}$$

$$K\dot{\gamma}^n = \tau - \tau_y \text{ if } \tau \geq \tau_y \tag{4}$$

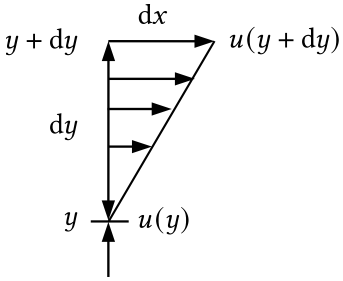


Figure 3: Kinematic relationship between the shear rate ($\dot{\gamma}$) and the velocity gradient in this configuration, $\mathrm{d}u/\mathrm{d}y$

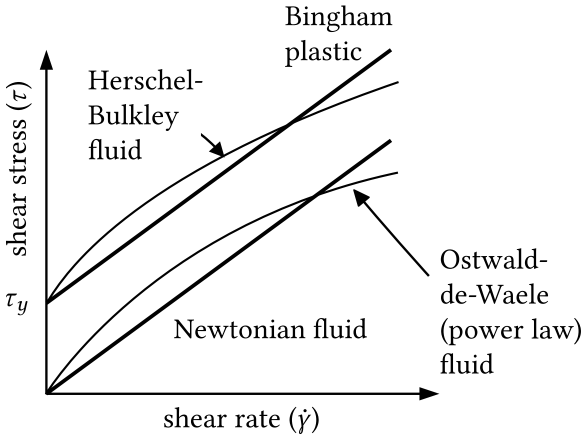


Figure 4: Most commonly used time-independent flow curves models used in long-distance pipe transport

where $\tau_y \geq 0$ and, in the case of pulps, concentrates, and tailings, $0 < n \leq 1$. When $n < 1$ and $\tau_y > 0$, Equations 3 and 4 define the so-called Herschel-Bulkley model, with K and n denoted as consistency coefficient and flow index, respectively. Other relevant cases to pipeline long-distance transport are:

$$
\begin{aligned}
(\tau_y, n) = (0, 1): &\quad \text{Newtonian fluid} \\
\tau_y = 0,\ n < 1: &\quad \text{Ostwald-de Waele (power law) fluid} \\
\tau_y > 0,\ n = 1: &\quad \text{Bingham fluid}
\end{aligned}
$$

Because of its simplicity for engineering calculations, the Bingham model is the most widely used. In this case, $K = \eta_B$ and is called Bingham viscosity (but unlike K, it actually has the units of dynamic viscosity). The extrapolative nature of the parameter determination has the natural consequence of rendering the yield stress obtained using the Bingham model higher than those using the Herschel-Bulkley model (*e.g.*, as depicted in Reyes et al., 2019, in the case of magnetite tailing rheology measurement). However, this particular characteristic is often used as an additional means for conservative pipeline design: higher yield stress defines higher flow requirements for laminar-turbulent transitions. It is therefore important to note that in the context of long-distance pipeline design (and given the commonly available instrumentation for characterization), the yield stress should be looked at as a design parameter rather than as a physical property (for instance, Barnes, 1999, shows, using an extremely sensitive rheometer, a case where the yield stress is a spurious interpretation of a flow curve with a sharp increase of viscosity at very low shear rates).

The key to slurry concentrate handling is that there is a strong relationship between particle concentration and rheological parameters. In particular, increasing concentrations implies linear, exponential, or super-exponential increase of viscosity, according to the range of concentration (the reader is referred to the review by Stickel and Powell, 2005, for a discussion on the role of concentration on the viscosity of suspensions when hydrodynamic effects are dominant over colloidal ones). In the case of the viscosity, common empirical ad hoc relations used in an engineering context for moderate to high concentrations (C_V) include the polynomial ($\eta_r = AC_V^B$), exponential [$\eta_r = A10^{V_r}$, with $V_r = C_V/(1 - C_V)$], and Krieger types:

$$\eta_r = \left(1 - \frac{C_V}{C_{Vm}}\right)^{-[\eta]C_{Vm}} \tag{5}$$

Here $\eta_r = \eta/\mu$ (μ is the liquid phase viscosity), and $[\eta] > 0$ and $C_{Vm} > 0$ are the intrinsic viscosity and maximum packing concentration, so when $C_V \longrightarrow C_{Vm}$, them $\eta_r \longrightarrow \infty$. Here, the parameters $[\eta]C_{Vm} = 2$ and $C_{Vm} \approx 0.48$ give a good fit to some copper and iron ore slurries (Ihle, 2013).

The central concept in Krieger-type relations is the assumption of a transition from fluid-like to solid-like behavior (the polynomial approach is in this sense physically inconsistent because yields display finite viscosities near the unrealistic particle concentration limit $C_V \longrightarrow 1$). In addition to its application to the determination of viscosity, the Krieger-type concept can also be used to model yield stress. Indeed, similar relations to Equation 5 are available in the literature to model yield stress-concentration relations, including that proposed by Heymann et al. (2002):

$$\tau_y = \tau^* \left[\left(1 - \frac{C_V}{C_{Vm}}\right)^{-2} - 1\right] \tag{6}$$

where τ^* is a fitting parameter.

A second important aspect that controls the rheology of suspensions is the particle size and distribution of particles in the suspension. A general trend is to find higher values of both the viscosity and the yield stress increasing the fine particle content for a fixed concentration. This, in conjunction with the effect of the concentration, can be seen schematically in Figure 5 on the following page.

The determination of the rheological parameters is central to the determination of power requirements of long-distance pipelines and is normally done using precision instruments that impose a simple flow configuration that enables a simplification of the stress tensor that describes the constitutive behavior of the slurry (Alderman and Heywood, 2004, present an interesting summary on the topic). The preferred means of assessing such rheological parameters in long-distance pipelines is by using concentric cylinder rheometers (Figure 6 on page 9), which enables obtaining indirect measurements of the yield stress and the rest of the flow parameters, depending on the model to be used, by sequencing $\dot{\gamma}$-τ curves. However, it is also common to use a vane accessory to solely measure yield stress and thus obtain an independent measurement of τ_y, Figure 6a shows a rotational rheometer, with the cup, a vane accessory for yield stress measurement, and a sand-blasted cylinder for flow curve measurement (Figure 6b shows the detail of the cup and bob array).

4. Hydraulics

In this section, the most important hydraulic elements of long-distance pipelines are discussed. This section requires an elementary knowledge of fluid mechanics. Nonetheless, key concepts are also reviewed.

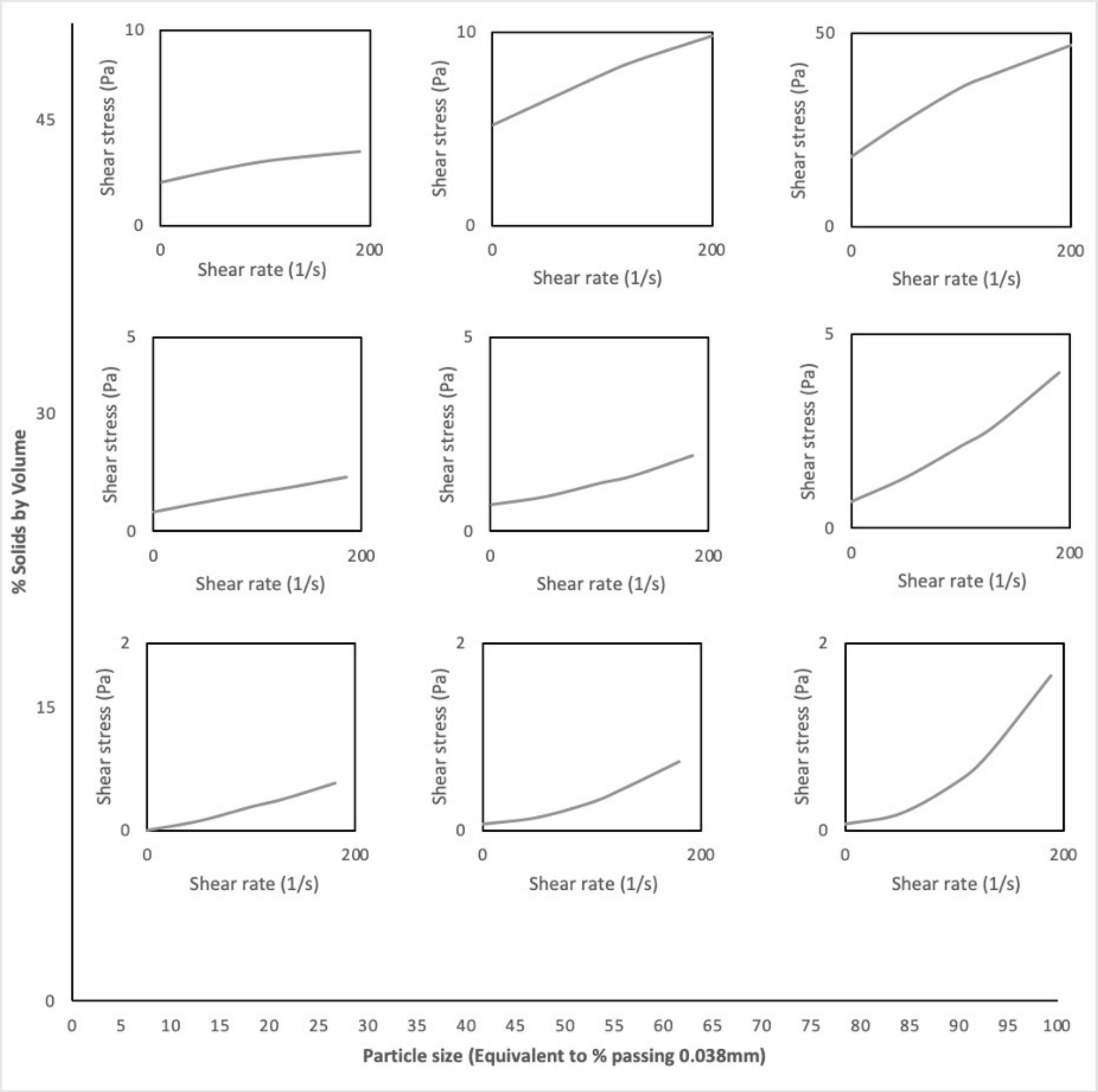


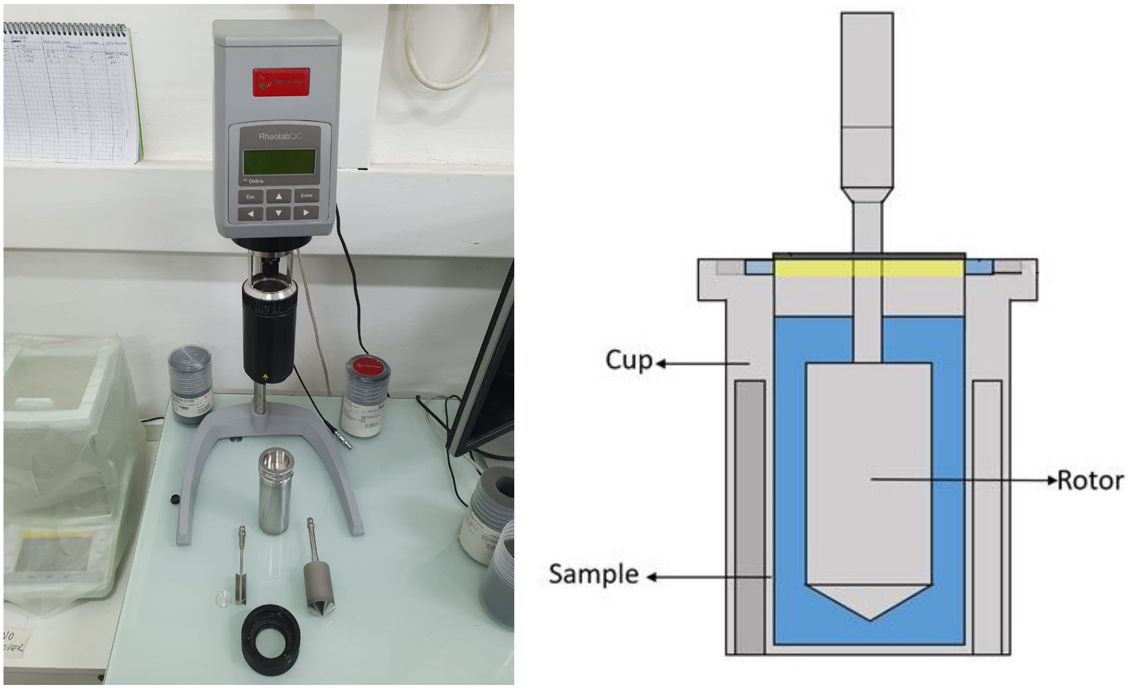
Figure 5: Combined effect of fine content and concentration (adapted from Shi and Napier-Munn, 1996)

4.1. Mass balance

Long-distance pipelines use water as a means of transportation of solid particles. Consequently, the water phase is not a process product in itself, but rather part of the footprint of the system. The key mass balance parameter in a long-distance system is the throughput (G), which corresponds to the solid phase flow. This is conveniently expressed in terms of the bulk volume flow as:

$$G = \rho_p Q C_V \tag{7}$$

From the definition of volume fraction (Equation 1) and the bulk flow (Q), it is straightforward to see that the volume flow of the solid phase (Q_p) and that of the fluid phase (Q_f) are $C_V Q$ and $(1 - C_V)Q$, respectively.



(a) Typical installation of a concentric cylinder rheometer

(b) Mid vertical plane schematic of the rotor unit fitted below the control unit

Figure 6: Concentric cylinder rheometer

4.2. Head

From an energy standpoint, long-distance slurry pipelines share some features with long-distance water pipelines. In particular, solid-liquid mixtures are seen as an equivalent fluid, as long as the slurry remains homogeneous (conditions for which will be mentioned later in this section).

4.2.1. Total energy head and piezometric head

The equivalent fluid notion allows the use of homogeneous, time-independent rheology concepts to compute the hydraulic gradient. The sum of the mechanical and internal energy in a specific point of an isothermal fluid stream that can be conceptualized using the definition:

$$H = \frac{p}{\rho g} + z + \frac{v^2}{2g} \tag{8}$$

where p and ρ are the relative pressure and density of the equivalent fluid in the pipeline, respectively, z is the altitude of the point of interest, g is the magnitude of the acceleration of gravity, v is the slurry mean flow velocity, $v = 4Q/\pi D^2$ (circular pipe cross section assumed), and D is the internal pipe diameter. Thus, H has units of length, and is denoted as the *total head*. The curve consisting of $H(x)$ ($0 \leq x \leq L$, where L is the tube length) corresponds to the *total energy line*. In long-distance slurry pipelines, mean flow velocities are often between 1 m/s and 2 m/s, depending on the pipeline diameter and solid phase properties. Because the solid-liquid mixture runs in natural topography, it is most common that pressures are several times that of the atmosphere and can be as high as 10 000 kPa at pump stations or at low points. In this case, the third term of the right side of Equation 8 (corresponding to the kinetic energy) is generally negligible when compared to the first two (which by definition form the *hydraulic grade line* [HGL]). This corresponds, pointwise, to the *piezometric head.* Therefore, in general, in long-distance slurry pipelines, both lines are quantitatively and essentially the same. A graphical interpretation is given in Figure 7, where it is noted that the pressure head, corresponding to the first term of the right side of Equation 8, is the line segment connecting the energy line and the terrain, whose corresponding head is z. This particular case is exemplified as $p_0/\rho g$ in Figure 7, where there is also a schematic representation of the pump and total head at the tube length location $x = 0$ (H_p, and z_p, respectively). The values of altitude (z_0) and pressure head ($p_0/\rho g$) are evaluated at the tube length position $x = x_0$. The total head at the pump location ($x = 0$) is $H_0 = H_p + z_p$, where z_p, is the altitude at $x = 0$.

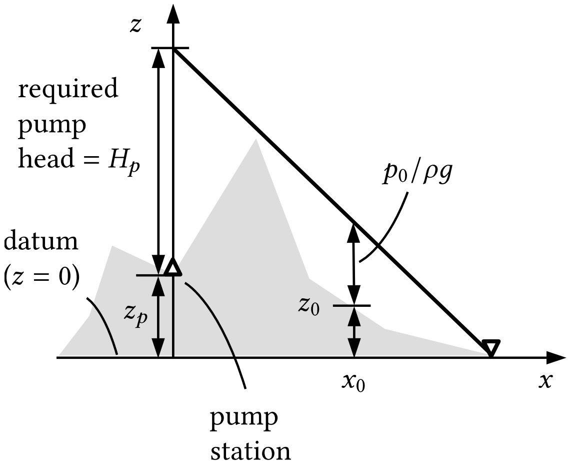


Figure 7: Energy component interpretation of the energy line in long-distance pipelines, assuming negligible kinetic energy head

If the bulk flow to be pumped (Q) is known, then the hydraulic power required to sustain such a hydraulic line is given by $P_h = \rho g H_p$. This is transferred with an overhead to the pumping system provided that the latter has an overall efficiency η_p to:

$$P_p = \frac{\rho g H_p}{\eta_p} \tag{9}$$

4.2.2. *Singular and regular friction losses*

Assume a long-distance pipeline of length L. In the absence of intermediate energy inputs, choke stations, and turbines, it follows that the difference between the pressure head at the initial and the final point (tube length coordinates position $x = 0$ and L, respectively) corresponds to the total energy losses:

$$H_0 - H_L = \Lambda \tag{10}$$

where Λ corresponds to the total pressure head losses. Pressure head losses can be classified as regular and singular. While the former are proportional to the tube length, the latter are associated with pipe singularities including valves, T-junctions, elbows, and such. A comprehensive account for singular losses can be found in the compendium by Idelchik (2008).

When operating in steady state, the hydraulic gradient is defined as the slope of the energy line:

$$J = \frac{\mathrm{d}H}{\mathrm{d}x} \tag{11}$$

where x is the tube length coordinate. In general, long-distance pipelines are built without singularities and thus have negligible singular pressure head losses. If the fluid flows homogeneously in the pipeline, regular pressure head losses can be accounted for using the Darcy-Weisbach equation:

$$\Lambda_r = f \frac{L}{D} \frac{v^2}{2g} \tag{12}$$

By definition, the. Darcy friction factor (not to be confused with the Fanning friction factor, f_F, where $f = 4f_F$) is:

$$f = 8 \frac{\tau_w}{\rho v^2} \tag{13}$$

where τ_w is the shear stress at the pipe wall. In the case of water or other Newtonian, viscous fluids, the Darcy friction factor can be readily computed using the Moody diagram, which compiles a number of relationships either for laminar or turbulent flow, where the single controlling parameter is the Reynolds number, $Re = \rho v D/\mu$ (*i.e.*, hydraulically smooth turbulent flow), or turbulent flow where frictional losses are additionally a function of the hydrodynamic roughness of the pipe's internals (Granger, 1987; Brown, 2002). Available models for the estimation of the friction factor in homogeneous non-Newtonian fluids can be found for laminar flows (Wasp et al., 1977; Ihle and Tamburrino, 2012) and turbulent flows (*e.g.*, Wilson and Thomas, 1985; Thomas and Wilson, 1987; Chilton and Stainsby, 1998). The use of the Darcy or the Fanning friction factors depends on the applicable community. While in chemical engineering circles the Fanning friction factor (which is, by definition, the wall shear stress-slurry kinetic energy per unit volume ratio) is customary, in hydraulic engineering parlance the Darcy friction factor is more commonly used. Although in process engineering when associated with mining infrastructure, both definitions could be found, the Darcy friction factor is more widely used.

Being comminution products, concentrates and a significant proportion of tailings have little content above approximately 200 µm, and thus behave as quasi-homogeneous mixtures in turbulent flow conditions. However, there are cases when transporting particles of several hundred microns in size is necessary, where it is no longer valid to assume that concentration is constant throughout the pipe section (both opposites are shown by Kaushal, 2002, who present measured concentration profiles for mean flow velocities above 2 m/s and particles between 38 and 739 µm).

Perhaps the most widely used model for this heterogeneous flow condition is that proposed by Wasp et al. (1977), who split pressure losses consisting of fine particles (and the liquid phase), and a bed (consisting of the coarse fraction being transported). To decide how the masses are split, they used a relation, derived by other authors in a river flow mechanics context, in terms of the settling velocity of particles, two empirical constants related to turbulent diffusion, and $\sqrt{\tau_w/\rho}$ (*i.e.*, the so-called *friction velocity*), thus posing an implicit problem on the friction factor that is solved after a few iterations. Alternative approaches for strongly stratified particle flows include those proposed by Karabelas (1976), Gillies et al. (1991), and Doron and Barnea (1993). Kaushal (2002) suggest that both the Wasp model and the Karabelas model can be improved by rendering both the turbulent particle diffusivity constant and the settling velocity concentration dependent.

4.2.3. Chokes and pump stations

Neglecting singular head losses, from Equation 10, $\Lambda = \Lambda_r$, for every pipe segment j, then $L_{j-1} \leq x \leq L_j$ ($j \in \{1, \ldots, N\}$), from Equation 12, the hydraulic gradient downstream of a pump station or energy output point (such as a choke station or a turbine) is given by:

$$J = \frac{f}{D} \frac{v^2}{2g} \tag{14}$$

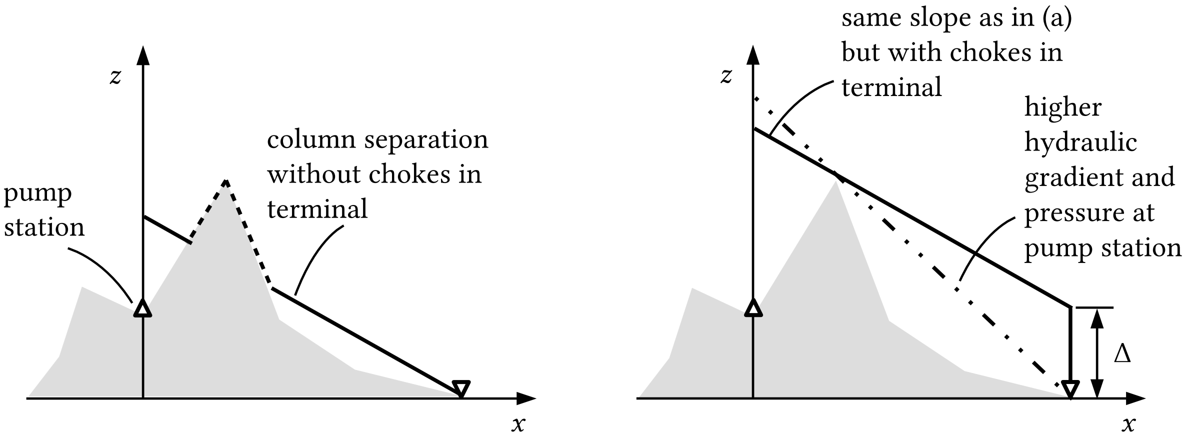
where the variables f, v and D are assumed constant within the segment. The corresponding (straight) energy line for such segment j has the form:

$$H_j = H_j^{(0)} - J_j(x - L_{j-1}) \tag{15}$$

with $L_{j-1} \leq x \leq L_j$, $j \in \{1, \ldots, N\}$ and

$$J_j = \frac{f_j}{D_j}\frac{v_j^2}{2g} \tag{16}$$

Chokes are singular head losses that are intentionally put at specific points of the tube length to ensure that the system is subject to positive pressure (*i.e.*, away from the vapor pressure threshold) at every point in the pipeline, and thus avoid slack flow. Figure 8 shows a case when including a point dissipation in the system (of magnitude Δ) is desirable to avoid liquid phase vaporization and negative relative pressure inside the pipeline (Figure 8a). A negative pressure inside the pipe may represent failure risk when there is a plastic liner mounted inside the tube. The representation of a (suboptimal) hydraulic solution to this problem using a higher flow, albeit without point dissipation, is depicted in the dot-dashed line of Figure 8b. This is associated with higher energy losses and, ultimately, a higher pumping power requirement, as seen by the higher intercept with the z-axis than in the case with chokes.



(a) Without chokes. The dashed line represents slack flow condition.

(b) With chokes

Figure 8: Effect of chokes on the position of hydraulic grade line. The gray area denotes the natural topography.

Although there are many long-distance pipelines (200 km or less that feature a single pump station, it is common that (due to pipeline high-pressure limitations) two or more pump stations may be required to split the energy line in two or more lower-pressure segments. Likewise, a very hilly topography may require two or more choke stations to optimize pumping and, ultimately, infrastructure investment.

Consider the schematic view of an HGL of Figure 9 on the following page, showing a jump on the energy line at $x = L_{j-1}$ ($j \in \{2, \ldots, N\}$). This is explained by the presence of a pump or choke station at that point. If the upstream pressure of segment $j - 1$ is known and equal to $H_j^{(0)}$, then the corresponding head jump is given by:

$$\Delta_{j-1} = H_{j-1}^{(0)} - H_j^{(0)} - J_{j-1}(L_{j-1} - L_{j-2}), \tag{17}$$

with $j \in \{2, \ldots, N\}$. From this equation, it is seen that Δ_j can be positive if the singular point is a choke station (*i.e.*, there is a drop on the energy line) or negative if it corresponds to a pump station (*i.e.*, a discontinuous increase).

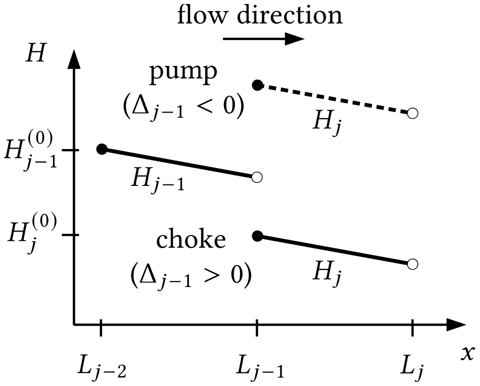


Figure 9: Hydraulic grade line with a discontinuity at L_{j-1}

4.3. Flow conditions for long-distance slurry transport

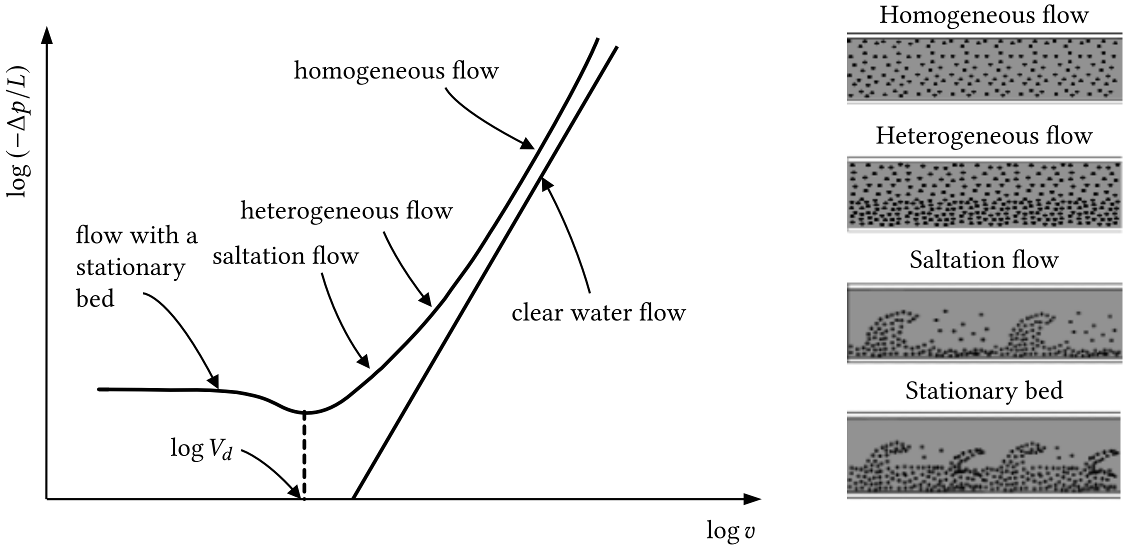
Long-distance pipelines, flowing in cross-country conditions, are most commonly settling slurries and operate in turbulent flow. This warrants that most or all particles are kept in suspension. There is evidence of attempts to operate long-distance slurry pipelines in laminar flow, which has resulted in both catastrophic and encouraging results (Paterson, 2012). The hypothesis that the ability to keep particles in suspension in laminar flow strongly depends on a sufficiently high yield stress and the magnitude of the pressure gradient in the pipe has been applied in paste backfilling distribution pipelines, which most commonly operate at distances in the order of a few kilometers long.

Figure 10 on the next page shows a typical relationship between particle concentration, mean flow velocity, and hydraulic gradient. For high-flow velocities, which are associated with strong turbulence fluctuations, particles are kept in suspension (Figure 10b). This corresponds to the so-called homogeneous flow regime. Decreasing flow causes particles to reach an equilibrium distribution, with their center of gravity below the pipe centerline, albeit with all particles in motion. This corresponds to the heterogeneous flow condition and is associated with the second schematic in 10b.

By decreasing the mean flow further, there is a critical point/condition where some particles keep in contact with the pipe bottom (first moving, exerting a dynamic friction force to the pipe bottom and, at a lower mean flow velocity, forming a static bed). Such critical condition is called the deposition limit. In the flow velocity-hydraulic gradient curve of Figure 10a, this is represented as the flow velocity that minimizes the hydraulic gradient. The deposition velocity V_d, can be roughly interpreted as the mean flow velocity representing the kinetic energy of a fluid parcel of volume V_p, and density ρ_f required to lift a particle of the same volume (and density ρ_p) a distance equal to the internal pipe diameter (D). The immersed weight of the particle is proportional to $(\rho_p - \rho_f)gD$, so it follows that $\rho_f V_d^2/2 \sim (\rho_p - \rho_f)gD$, and thus

$$V_d \sim \sqrt{2gD(S-1)} \tag{18}$$

Saltation flow is defined by Niño and García (1998) as *the unsuspended transport of particles over a granular bed by a fluid flow, in the form of consecutive hops that nonetheless keep the particles within the near bed region, which is governed mainly by the action of hydrodynamic forces that carry the particles through the flow, the downward pull of gravity, and the particles' collision with the bed.*



(a) Regular friction losses

(b) Particle flow regime in the pipe section

Figure 10: Behavior of the effect of particle segregation (adapted from Turian and Yuan, 1977)

In Equation 18 and above, the sign '$\sim$' stands for an order of magnitude but requires dimensional homogeneity. That is, what is to the left of '$\sim$' must have the same units as the expression on the right. The scaling given by Equation 18 does not take into account interactions between particles (*i.e.*, the effect of concentration and the particle size distribution [PSD]) or the drag force between the particle and the fluid, which depends on the particle size. Therefore, $V_d/\sqrt{2gD(S-1)} = F_L(d_p, C_V, \text{PSD}, \ldots)$, which is called the Durand correlation, where F_L, (Durand factor) is a dimensionless function of combinations of the aforementioned parameters (Miedema, 2016, gives a complete review of empirical models to compute F_L). In particular, because the notion of deposition velocity relies on additional variables other than the pipe diameter and fluid properties, dimensional analysis dictates that the deposit formation condition is, in general, different from the laminar-turbulent flow transition condition. It is evident from Figure 10a that an operation at a slurry flow corresponding to the deposit velocity limit (or below it) will imply failure of the objective of transporting particles. In cases when there is a requirement to operate below such minimum operational limit (especially during the initial periods of the mine production), a batch operation between slurry and water is required, which will significantly increase the water consumption. As an example, a 100 km-long pipeline with 5 in SCH 80 nominal diameter (internal diameter 12.2 cm) has an internal volume of 1172 m^3.

4.4. Design condition and operational diagram

Without taking into account a paste flow design approach (as referred above), common long-distance pipeline hydraulic design approaches need to ensure that:

- Mean flow velocity is above the deposit velocity limit
- Flow regime is turbulent
- The pipe diameter is such that overall costs are minimal
- Inclined sections (either negative or positive) are within specified limits

Laminar-turbulent flow transition in slurry flows has been modeled empirically by a number of researchers since the mid-1950s. Perhaps the most widely accepted criterion to estimate such condition is the model proposed by Hanks (1963), which requires the knowledge of the (Bingham plastic) rheological parameters and pipe internal diameter.

The effect of inclined sections is twofold. First, compared to the horizontal case, inclined sections cause an increase in frictional losses in the upslope section (and a decrease of frictional losses in the downside section) when compared to the horizontal case. Depending on the particle size and flow conditions, such an effect can be significant (*e.g.*, Doron et al., 1997, show this effect in terms of the angle on coarse particles). Conversely, and most importantly, inclined sections are related to the accumulation of particles at local minimums of the pipe route. Cross-country pipelines are almost inevitably marked by the presence of local minimums and maximums. When planned stoppages or unintended system shutdowns occur (such as following system failures or blackouts), particles will inevitably migrate in the downslope sections. Depending on the combination of stopping time, particle concentration, section length, and inclination, particles will organize themselves, creating a heterogeneous flow consisting of a (potentially static) particle bed, a slowly flowing layer above the bed and an upslope clear fluid layer resulting from mass conservation.

If the average pipe slope section is too high, then there is the potential for slurry bed sliding or bulk migration toward the bottom section, which will eventually generate a slurry plug at the bottom section. Conversely, due to the almost static friction force between the slurry and the pipe wall, the pressure force required to restart a plug section is higher than that required when there is a clear section available for solid resuspension from top to bottom. This is shown in the sequence of Figure 11 on the following page. The steady bed condition shown in Figure 11a rapidly evolves to the formation of billows and turbulent structures with subsequent strong mixing (Figures 11b to 11e). About 4 seconds after the system starting up (Figure 11f), the solid context is almost fully mobilized.

Depending on the length of plug sections, there is the potential for a system failure due to overpressure, departing from steady and transient operation design values, either on the pipe wall upstream of the plug or on the pump casing (if the potential of plug formation is not anticipated). Designers often consider three control measures in this regard:

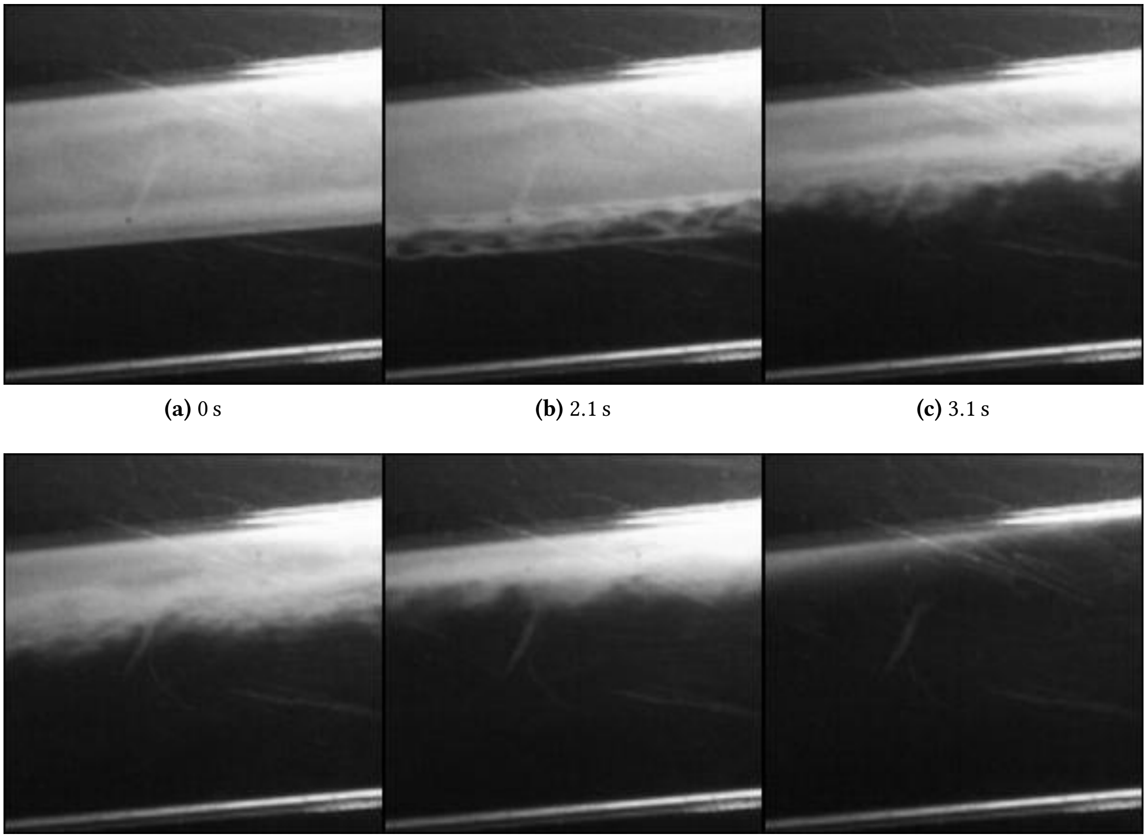
Limit the section slopes It is common practice to set them below 15 %–18 % in slope, but final restrictions will depend on results obtained from angle-of-repose and angle-of-slide tests. The angle of repose corresponds to the steepest angle of the granular material, relative to the horizontal plane, to which the material can be piled without particle slumping (*i.e.*, corresponds to limiting static condition of a pile). Conversely, the angle of slide corresponds to the minimum angle of the pipe axis, measured from the horizontal, at which a particle bed will start to move toward the bottom.

Limit maximum stopping times An estimation is commonly obtained from a set of pipeline start-up-rest-startup tests during the commissioning stage.

Limit particle concentrations This is an indirect way of limiting downslope mass flow.

A typical *operational diagram* looks like Figure 12 on page 17, and represents the locus of feasible operational conditions considering the above limits and the following mechanical constraints:

- Maximum pressures the pipe can withstand
- Maximum effective flows the pumping system can deliver



(a) 0 s **(b)** 2.1 s **(c)** 3.1 s

(d) 3.2 s **(e)** 3.5 s **(f)** 4 s

Figure 11: Resuspension experiment of copper sulfide tailing, showing the particle resuspension sequence departing from the initial state of fully settled material for a 150-cm pipe of sloping section of 8 %, with a clear fluid velocity above the particle bed of about 2 m/s. Here, $C_V = 0.28$, $S = 2.7$, $P_{80} = 70$ µm (adapted from Ihle et al., 2011).

The operational diagram is customarily expressed as an x-y plot with the flow rate (Q) on the x-axis and the system throughput (G) on the y-axis. The various curves that cross the shaded region correspond to zones of constant solid phase concentration. In this diagram, the low-flow limit is associated with velocities below the deposit limit, while the high-flow rate is related to operational pressures above maximum due to the energy available from pumps or elevation level or transient allowable value, and thus are related to pressure relief device activation (either rupture disks or pressure relief valves, as referred to in Section 5 on page 18). Conversely, increasing G at constant values of Q causes, by virtue of mass balance (Equation 7), an increase in C_V, which increases the friction factor and therefore operational pressures inside the pipe, thus expanding the upper limit of operation.

4.5. Specific energy and economic condition for transport

The specific energy consumption (SEC) is defined as the energy required to transport a unit mass of solids per unit length. In a pipeline with a consistent diameter, from Equations 7 and 10, this corresponds to the ratio of total consumed power per unit pipe length, $\rho g Q \Delta H/L$ (H is measured in

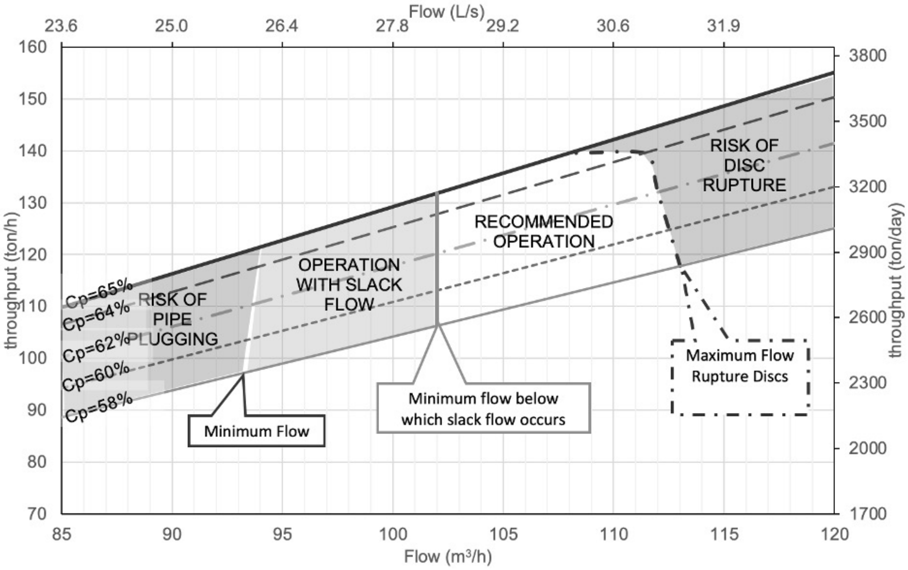


Figure 12: Operational diagram of a long-distance slurry pipeline.

slurry head units), and the solids phase mass flow, given by Equation 19:

$$\mathrm{SEC} = \frac{\rho g \Delta H}{\rho_s C_V L} \tag{19}$$

Experimental work supports that, given a pipe diameter and solid concentration, the flow velocity that minimizes the SEC is the deposit velocity (Wu et al., 2010, and references therein). This is, however, a marginal condition that, under flow fluctuations or substandard PSD, might cause a particle bed formation to occur.

Fixing the throughput and assuming the slurry behaves as a (quasi-)homogeneous mixture, in the limit of small concentrations the friction factor converges to that of water and for any positive pipe diameter (Equation 19) it diverges. Increasing the particle concentration (while the rest of the variables are kept fixed) will induce an increase of the wall shear stress that competes with the term $1/C_V$ in Equation 19. In the limit of high concentration, and given typical conditions of long-distance transport, $\mathrm{dSEC}/\mathrm{d}C_V > 0$ (Ihle, 2016), and therefore there is an optimal concentration that minimizes the SEC. This concentration is often very high and may therefore be chosen as the highest possible concentration that ensures safe hydraulic transport in the sense of avoiding pipe plug formation in the event of system shutdown. Conversely, assuming that the friction factor is a slowly increasing function of the pipe diameter (*e.g.*, $f \propto D^a$, with $a = 1/4$ for Newtonian fluids according to the empirical fit by Blasius (1912), then the SEC tends to decrease with the pipe inside diameter. Because the pipe cost is an increasing function of the pipe diameter (*i.e.*, a larger pipe diameter reduces the SEC but increases the capital cost) and that (from Equation 18) the deposit velocity roughly increases with $\sqrt{D}$, there is also an optimum for the pipe diameter. Based on this concept, a set of simplified formulas for the determination of the economic pipe diameter of settling slurries has recently been proposed as the result of the minimization of a water, energy, and pipe cost function, resulting in optimal diameters that are proportional to either $\sqrt{G}$ or $G^{3/7}$ depending on how the relationship between a pipe's inside diameter and its thickness is modeled (Ihle, 2020).

5. Infrastructure

In its most simplistic terms, the infrastructure associated with long-distance transportation by pipeline consists of pumps, pipes, holding tanks, and chokes.

5.1. Overview

Figure 13 shows a typical flow sheet of a long-distance pipeline system. It consists of the following main components:

- Storage tanks and slurry dilution system
- Pumping system
- Pipe system
- Choke station
- Emergency devices and infrastructure

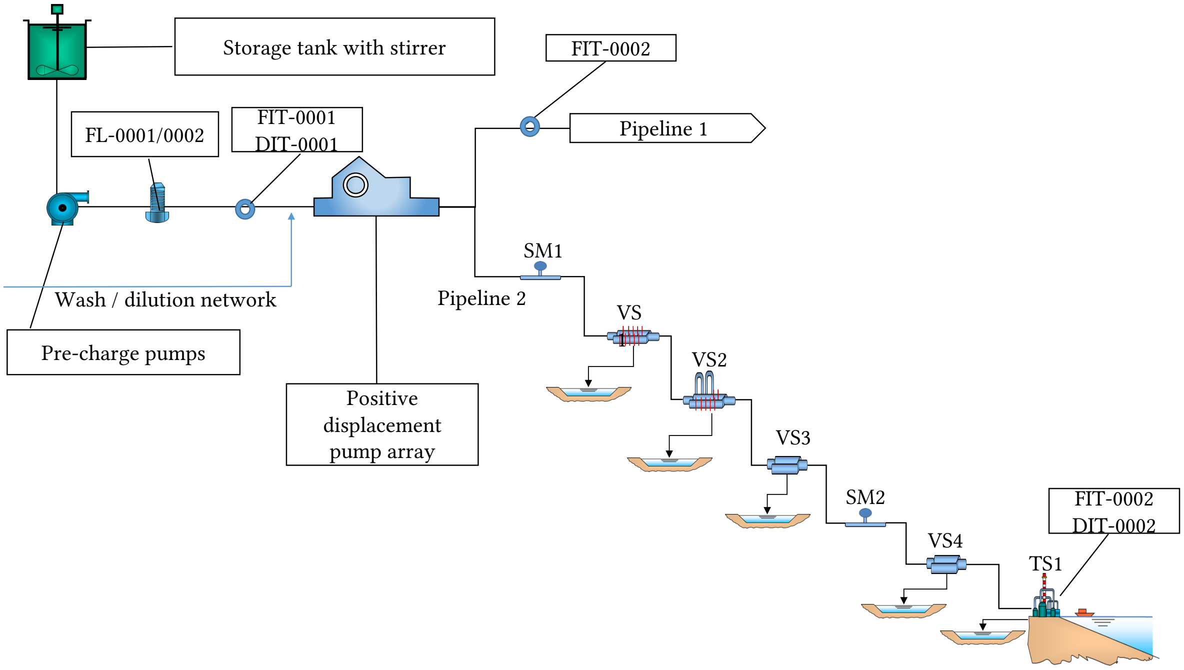


Figure 13: Flow diagram of a long-distance pipeline system with typical components and infrastructure

5.2. Holding (storage) tanks and slurry dilution system

Prior to suction into the pumping system, the slurry is stored in agitated holding tanks. This has the functions of keeping particles in suspension, homogenizing the stream, and acting as an accumulation point for some hours in case of required maintenance of the pumping system with sustained upstream slurry delivery. Holding tanks require a continuous stirring system to enable effective particle resuspension and normally have baffles to facilitate vertical flow. It is also common that they have a sampling system for slurry composite generation (upstream of the tank) and a flush valve downstream.

(a) Elevation view

(b) Stirrer view from above

Figure 14: Holding tank

Figure 14 shows a picture of this kind of infrastructure. In colder regions heating systems might be required to be included in the tanks.

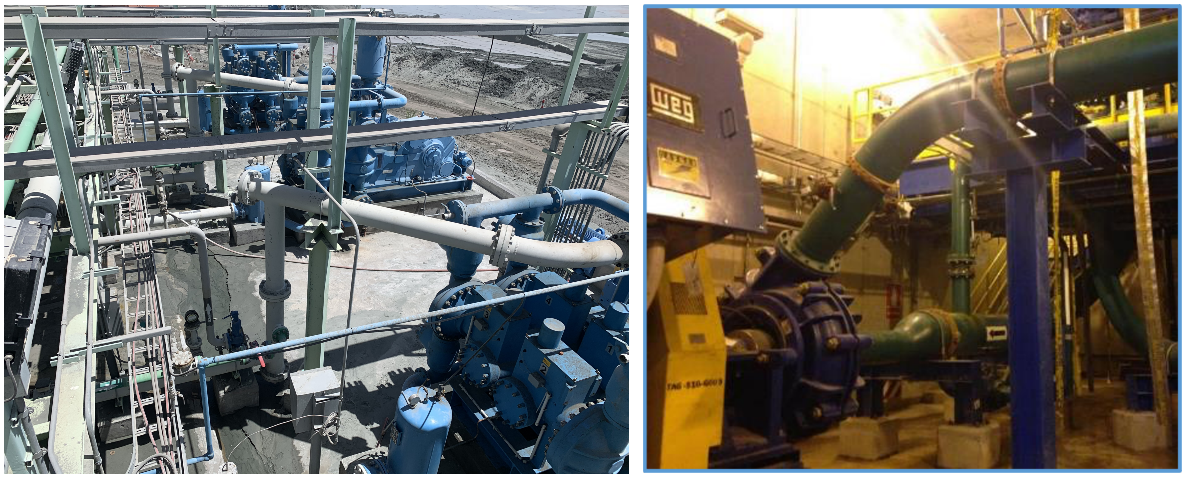
After the slurry is discharged downstream from holding tanks, there is often the need to adjust the slurry concentration to fit the design values. This is done using a dilution loop, where a control valve sets the water flow that blends with the main slurry stream.

5.3. Pumping system

For the mainline pumps of long-distance slurry pipelines, positive displacement pumps (called PD pumps hereafter) and centrifugal slurry pumps are generally used.

Usually when the required pump station's discharge pressure is less than about 650–700 psi (4.5–5.0 MPa), centrifugal pumps are used because of their economic advantage over PD pumps. When the required discharge pressure exceeds the pressure a single pump can deliver, multiple pumps can be installed in series. In this case, a backup train of pumps must be installed to allow for maintenance purposes.

For systems requiring discharge pressures in excess of 700 psi (4.9 MPa), PD pumps are usually used. Nowadays, for long-distance pipeline slurries, which are generally medium abrasive, PD pumps of the piston-diaphragm type are widely used for pressures up to American National Standards Institute (ANSI) Class 1500 psi (9.3 MPa). If PD pumps are used, centrifugal charge pumps must be installed to satisfy the PD pumps' suction pressure requirements. Figure 15 on the next page shows a facility with PD pumps (Figure 15a) and an example of an upstream charge pump (Figure 15b).



(a) Piston-diaphragm slurry positive displacement (PD) pump (blue equipment)

(b) Charge pump connected upstream of a PD pump

Figure 15: Typical pumping system for long-distance slurry pipelines

5.4. Pipe systems

Long-distance slurry pipes are commonly buried, rendering them unobtrusive, and also because, in some cases, this can preclude theft or sabotage. They are generally designed to provide a long service life; therefore, the pipes need to be protected from corrosion and abrasion to avoid or mitigate the metal loss.

To avoid external corrosion related to soil moisture, the steel pipes are commonly wrapped with high-density polyethylene (HDPE). A chemical means of protection may also be employed (see Section 7 on page 26) if the slurry is highly corrosive or abrasive, in which case the steel pipes may need to be internally lined with HDPE, rubber, or polyurethane (PU). HDPE liners, often used in long-distance copper concentrate lines, are used when the slurry flow velocities are not very high (less than 5 m/s) and the solids are not too coarse and do not have sharp edges. Rubber or PU, which are more wear resistant compared to HDPE, can be considered for very high-flow velocities or for very long design life of pipelines, especially in the transport of tailings.

Figure 16 on the next page shows a stub end with an HDPE liner internally mounted in a copper concentrate pipeline. The highest HDPE standard pressure rating is approximately 2200 kPa, which is usually unsuitable as a liner in a steel pipe for long-distance pipelines where pressure often exceeds 10 000 kPa at discharge points or low points (this feature is referred to in Section 4.2.1).

The fact of being long distance implies that this kind of pipeline has pressure losses that are relatively high when compared to those of water pipe systems. Pipes greater than a few kilometers in length also exist cross-country, where high and low points are associated with relatively low- and high- pressure zones, respectively, as discussed in the “Hydraulics” section. Thus, long-distance slurry pipelines are made of materials rated for high pressure, such as the American Petroleum Institute (API) standard for pressure pipes (commonly X65 grade). In some systems, the pipe thickness is adjusted to meet specific energy requirements while ensuring mechanical integrity. Due to the higher probability of logistic issues related to this design approach, constant-diameter and constant-thickness pipes are often used.

Figure 16: High-density polyethylene (HDPE) liner installation in copper concentrate pipeline. The inner ring consists of an HDPE stub end, tightly fitted into the steel, pressure-rated pipe.

5.5. Choke and valve stations

Choke stations can provide a fixed array of energy dissipation elements or a variable one to enable energy dissipation control under various flow conditions or a batch operation scenario. Choke stations are often designed to operate at high pressure rates, commonly up to ANSI Class 2500 psi (16.2 MPa). Each energy dissipation unit consists of a high wear-resistant disk (typically made of a ceramic material) with a small-diameter bore (Figure 17a on the following page), which causes hydraulic column drops on the order of 150-m equivalent slurry head. Their mount is flanged to ease maintenance while ensuring high-pressure service, and they normally last several years. The function of a single dissipation disk can be combined with multiple units bypassed by on-off valves, thus enabling a discrete number of dissipation combinations. This has the practical advantage of concentration-dependent dissipation steps to minimize energy consumption in the system. Figure 17b shows a typical choke station facility.

There are cases where no energy dissipation is required but, either for safety or operational reasons (the latter including a prolonged pipe shutdown, where the pipe is often filled with water), the fluid column is required to be split. To this purpose, valve stations with on-off valves are installed. It is common that choke stations are also valve stations.

5.6. Emergency devices and infrastructure

Pressure relief devices such as relief valves and rupture disks need to be installed at all stations, including pump and terminal station to protect the pipeline system from overpressures.

5.6.1. Pressure relief devices

Rupture disks are usually provided on the suction side of intermediate pump stations, valve stations, choke stations, or the pipeline terminal. They are non-reclosing devices consisting of a metal membrane that bursts at a specified pressure. Figure 17b shows a rupture disk mounted between flanges on a relief line at a valve station.

Pressure relief valves are generally installed on the discharge side of positive displacement pumps. This requirement applies to PD pumps because they deliver flow roughly independently of system pressure losses. In particular, this implies that if there is an obstacle in the pipeline that causes an increase of pressure upstream, a PD pump will keep imposing the flow (*i.e.*, it will keep pumping), thus causing an increase of pressure that may threaten the pipeline and the pump.

On the discharge piping of a PD pumps, vents and drains are provided to allow (for maintenance

(a) Choke bean (single dissipation element)

(b) Rupture disk (circled) on the upstream side

Figure 17: Choke station components

purposes) the release of the entrapped pressure.

5.6.2. Emergency ponds

An emergency pond needs to be installed in the pump station area for receiving slurry flushed from pumps and piping during maintenance. Also, when the slurry is not suitable for retreating or blending for pipeline transport, it must be diverted to the emergency pond too. At the terminal station, an emergency pond needs to be provided to accept slurries that are not acceptable for the downstream process (usually a filter plant).

Besides the common operational use of emergency ponds, it is common to locate one or more of these ponds at intermediate points to provide a means of flushing the slurry upstream of a rupture point in the line. Although there is no guarantee that spills will never happen, these ponds provide a means of minimizing environmental damage in case a failure does occur. The existence of emergency ponds needs to be complemented with active monitoring, such as leak detection systems.

5.6.3. Instrumentation

Instrumentation is key to ensuring normal operation, both for real-time monitoring purposes, for example, early detection of critical operational anomalies such as high pressures, and for slurry acceptance purposes as referred to in Section 3 on page 4.

For long-distance slurry pipelines, the main variables that are monitored in real time are volume flow (Q), slurry concentration (C_p or C_V, typically C_p), and pressure. Off-line monitoring or rheology, particle size distribution (PSD), and pH are also commonly conducted.

It is also relevant to measure rheology for pressure loss (and, ultimately, energy consumption) assessment and maximum operational pressure forecasting. While the former element is related to energy efficiency and carbon footprint, the latter directly affects operational stability because exceedingly high pressures may cause pipeline damage or trigger the activation of hydraulic safety elements, including burst disks (which then need to be immediately replaced after activation). The settling and abrasive characteristic of slurry flows represents a real challenge to the industrial implementations of online rheology measurement sensors, and mature technologies in this regard are still not universally employed or available. Therefore, it is common that in lieu of real-time monitoring technology, sampling and on-site laboratory measurements to validate slurry batches are undertaken. In some laboratories, settling velocities (*i.e.*, the velocity of the suspension-supernatant interface) using a probe tube are also monitored and compared with reference values as a means of determining acceptable transport conditions.

Volume flow is normally monitored using magnetic flowmeters, which compare an imposed magnetic field with a voltage difference signal induced by the flow in response. This kind of instrument actually measures the mean flow velocity, which is proportional to the volume flow. Magnetic flowmeters are mounted in-line and thus need to withstand the same pressure rating and chemical resistance as the pipeline. A drawback of this kind of instrument is that they are sensitive to the medium's electrical permittivity, which means that large fluctuations in the chemical properties of the slurries being transported may induce spurious fluctuations of measurements. A less widespread technology for volume flow measurement is the sonar-type sensor. These are noninvasive, so there is no need for them to be pressure rated because they do not rely on the slurry's electrical properties.

Particle concentration is relevant because of its relationship with rheology and its impact on system start-up, which is a critical factor in long-distance systems. The resuspension situation corresponding to start-up after system shutdown (shown in Figure 11) is only possible if there is a clear section where there is the potential for progressive resuspension via the shear stress exerted by the clear fluid layer on top of the sediment layer. This mechanism is hindered or eliminated at high concentrations if the pipe is plugged at a low point. Particle concentration is often monitored online at the suction side of the pump system using gamma ray densitometers. Recent nonradioactive alternatives have been developed and may find widespread application in future facilities. (Turning/rotation to reduce thinning of the pipe skin/wall is often used on shorter-distance pipelines with high solid concentrations, for example, high-density tailings transported between the Instrumentation concentrator plant and the tailings storage facility. In long-distance pipelines, which are most often buried, this is not common practice.)

Pressure is measured using online digital transducers, which are commonly of the piezoelectric type. They are essentially load-sensitive resistors, placed in a housing and isolated from the fluid stream by a diaphragm. For their use on facilities over long distances (like pipelines), electrical supply and redundancy need to be provided, as well as a local indication of measurements (*i.e.*, pressure indication and signal transmission [PIT] and sole pressure indication [PI] instruments). Pressure monitoring stations are often closed, sturdy facilities that are designed to contain potential piping bursts and leaks where the sensors are located. Because they are commonly located in areas where utility power is not available, they are self-power supplied using solar energy panels. Signals can be transmitted either via optical fiber or wireless mobile technology.

A critical variable that needs monitoring is the particle size distribution (PSD). An inadequate PSD might feature either too many fines or too coarse particle content. While in the former case, rheological parameters (*e.g.*, Bingham viscosity and yield stress) might be significantly affected (Figure 5), coarse content may preclude transport and resuspension with this material either remaining stagnant at horizontal sections or accumulating at low points with the potential of forming a plug. As in the case of rheology measurements, it is uncommon to use online PSD measurement instrumentation. Instead, PSD measurements are often made after extracting samples from the feed tank or charge pump suction line. Acceptance criteria vary, but they are often related to maximum percentages passing Tyler (or US) 100 mesh.

The most prominent measured chemical parameter for slurry transport is pH. Depending on the slurry being transported, low pH values may accelerate corrosion while high pH values promote the formation of precipitation scale within the pipe. This is often monitored in plant metallurgical laboratories as a means of validation of slurry transport feasibility. In case of substandard conditions, additives for pH modulation might need to be added.

6. Commissioning, starting up, and operation

The commissioning of a pipeline system consists of its testing prior to start-up and begins after the completion of mechanical works in the system. However, in practice, the whole system's construction usually cannot be completed before commissioning starts, for example, if the telecommunication system is not mechanically completed.

6.1. Commissioning

A commissioning manual is developed to provide the methodology and procedures for the commissioning of the pipeline system. The whole pipeline system commissioning can be broken down into two phases: precommissioning and commissioning. They are discussed in the following sections.

6.1.1. Precommissioning

Precommissioning is the phase when all the components within a system or subsystem can be energized and tested individually or as operational units. This phase ensures that the components are constructed as specified by project design and are functional.

Examples of checks that are made during precommissioning to validate the function of system components include:

- Systematic checks to verify the mechanical completion in compliance with the project drawings and specifications (including hydrostatic tests of station piping and pipeline)
- Energizing of pumps and agitators, as well as pressurization sections of the pipeline and conducting local starts, to confirm their operationality
- Repeated starting of motors through supervisory control and data acquisition (SCADA) system
- Local and remote operating of valves (including emergency and dump valves)
- Checking SCADA receipt of instrument output
- Calibration of instruments and SCADA signals

6.1.2. Commissioning

Completion of the precommissioning phase means that the overall system is ready for comissioning, when the overall system performance (including the hydraulic and control system) will be fully checked and fine tuned. In this phase, the working fluid of the pipeline is water. Tests made during the water commissioning will include:

- Loop tests at pump station
- Initial filling of the pipeline with water
- Pumping water from pump station to the terminal
- Hydraulic performance check of the pipeline system

- Performance check of SCADA and communications system
- Testing of automatic sequences including start-up, shut-down, choke changing, pump switch, throughput changing, and emergency procedures
- Returning of instruments for operating conditions

If the pipeline is not internally lined or coated, when pumping water, a sodium sulfite oxygen scavenging solution needs to be added to reduce oxygen content in the water.

6.2. Start-up

Once the system has been checked using water in the commissioning phase, the pipeline system is ready to operate with slurry.

An operating manual must also be developed to provide general technical information, as well specific instruction in the function, start-up, and operation of the pipeline and its related facilities.

Start-up will be commenced by initially introducing water into the pump station. When steady-state conditions are established, it can be switched to slurry feeding.

This phase of work includes:

- Filling of the pipeline with slurry
- Necessary final checks of pipeline system on slurry
- Performance tests of the pipeline system on slurry

Start-up tests conducted to prove that the pipeline system meets the performance guarantees of the design will include:

- Maximum throughput/concentration tests
- Minimum throughput/concentration tests
- Slurry density control with automatic or manual control

6.3. Operation

The pipeline is designed to operate continuously on slurry except during flushing of the pipeline for shutdown or batching operations.

Batch operation is the alternate pumping of slurry and water. This mode of operation is required to compensate for the production shortfall of the upstream process and maintain slurry flow above the minimum allowable velocity.

The pipeline operating includes the following main tasks:

- Pipeline normal start-up
- Pipeline restart on slurry
- Pipeline steady-state operation (including maintaining the slurry density and flow rate within the operational range, managing slurry inventory and if necessary, conduction of batch operation)

- Subsystem operations (agitators, thickener underflow pumps, charge pumps, mainline pumps, sump pumps, test loops, sodium sulfite and milk of lime systems, etc.)
- Pipeline normal shutdown
- Pipeline emergency shutdown
- Handling of abnormal situations such as pump failures, loss of power, loss of communications or PLC, pump overpressure or line rupture, and leaking
- Pipeline pigging

7. Pipeline integrity

The concept of pipeline integrity is a replacement of the traditional maintenance notion and is related to continuous action to minimize the occurrence of failures. Some common failure mechanisms and what kind of periodical operations can be done to detect and anticipate problems are described in this section.

7.1. Notion of pipeline integrity

For quite some time, the mining industry has been dealing with the problems and consequences caused by pipeline failures. Failures often result in environmental damage that may affect people that live near pipelines (*e.g.*, in the case of water or land contamination, or as a direct effect of flooding populated areas). They are very costly in the sense that they take considerable time and efforts to be fully identified and corrected. Any failure in a pipeline can trigger an entire check of the operation, and even lead to revoking licenses and even the closure of an operation. Furthermore, the reputational damage caused by a pipe failure can be considerable.

In addition, there are human and environmental impacts. A failure in a slurry pipeline may involve fatal events and environmental contamination, which can affect the livelihood of local habitants. Therefore, the study of pipeline integrity has become an indispensable topic for their proper design and safe operation. The evaluation of pipeline integrity consists of checking every element for its safe operation throughout its service life. These elements, in addition to the procedures and the frequency of verification, are the result of the previous analysis work conducted in the design phase such as HAZID, HAZOP, and bow tie (Crawley, 2020).

7.2. Common pipeline failure mechanisms

Thickness reduction due to corrosion and/or mechanical wear is one of the main common causes of pipeline failure. In slurry pipelines, the most common failure mechanisms are:

- External corrosion
- Internal corrosion
- Scale formation leading to higher pressure operation, detachment, and the potential for plug formation
- Corrosion under stress (CST) (*i.e.*, reduction of the wall thickness caused by the exposure of the pipeline to specific stress conditions)
- Bacteriological corrosion

- Soil corrosivity
- Soil movement
- Inefficient cathodic protection system
- Electrical interference (*i.e.*, electrical currents that can be captured by the duct due to specific events, including failure in the coating or liner, damage provoked by third parties, or natural damage such as lightning and storms)
- Pipeline abrasion

7.3. Integrity assessment and monitoring

To protect the duct from electrical corrosion, an efficient cathodic protection system, consisting of the connection of the pipe to a sacrificial anode —made of a more easily corroded metal— typically with a direct current (DC) supply, should be designed. This is depicted in Figure 18.

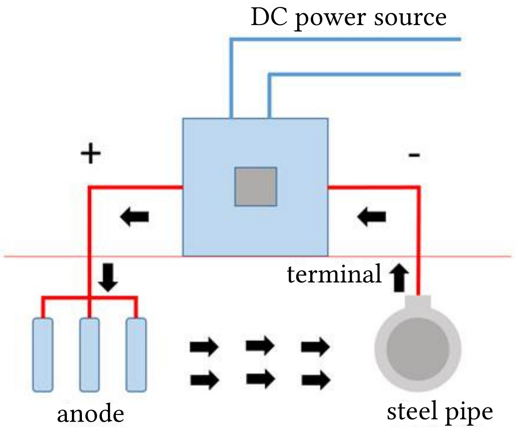


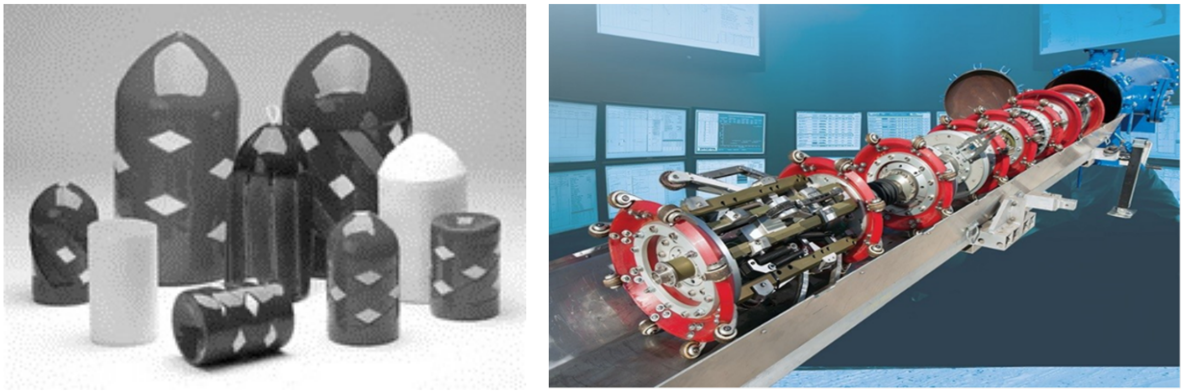
Figure 18: Typical cathodic protection system

To diagnose the integrity of a long-distance slurry pipeline, it is common to use pigs, which are cylindrical devices with a diameter slightly less than the internal diameter of the pipe, which are moved by the imposed pressure gradient. They can be used for a singularity check within the pipe or to help clean the pipe cross section, and thus are soft so they tear in the presence of obstacles or contain instruments to accurately measure pipe wall thicknesses when it is known (for certain) that the pipe section is clear of any obstacles. Figure 19 on the next page shows both types of pigs.

In slurry systems, mechanical abrasion is one of the most important factors that affect the life cycle of the project. Such impacts must be specifically verified during a pipeline's integrity study. During the pipeline system design stage, all the factors that can systematically change the system's life cycle (such as pumping velocity, granulometry, and hardness of the pumped mineral) should be accounted for.

For each parameter to be checked, a type of instrumented pig suitable for the correct verification should be used. For example, *geo pigs* are used for checking duct deformations, ultrasonic pigs for cracks, leak detection pigs, and so forth.

Instrumented pigs must be used to check the condition of the duct with a variable frequency depending on the kind of fluid or pumping system employed.



(a) Cleaning pigs **(b)** Instrumented pig

Figure 19: Pigs for pipeline integrity monitoring and cleaning pigs

Good engineering practice recommends that the interval between instrumented pig inspections should not exceed 5 years. Moreover, cleaning tools (*i.e.*, soft pigs) should be used to prevent the accumulation of sediments that could deteriorate the duct faster than designed.

For detection of defects in the duct coating, the following techniques can be used:

- Direct current voltage gradient (DCVG) inspection technique
- Inspection by current attenuation and potential step by step

The integrity assessment method must be selected according to the results of a risk analysis for each duct or duct system. Some approaches to this purpose include:

- Hydrostatic tests to verify whether the corroded duct withstands the maximum pressure required for its operation, and inspection in-line by using instrumented pigs
- External corrosion direct assessment (ECDA)
- Internal corrosion direct assessment (ICDA)

These procedures are further divided into preassessment, indirect assessment, direct assessment, and postassessment.

Integrity monitoring is often complemented by using leak detection systems. A number of algorithms have been adopted in long-distance pipeline systems, ranging from mass balance checking as a means of comparing flowmeter measurements upstream and downstream of the pipe, the incorporation of pressure losses via HGL monitoring combined with fuzzy logic algorithms (thus requiring pressure and flow information), and the use of artificial intelligence to discern between normal and anomalous operational scenarios, with similar input data requirements. A complementary approach for leak monitoring is the installation of a distributed sensor to detect local changes on the sensor properties when flooded by the slurry; an example is to use an optical fiber to sense abrupt temperature changes outside the pipe section. This can add to the aforementioned estimation of leak magnitude and the fast and accurate determination of its location.

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