CROSS-COUNTRY BAUXITE SLURRY TRANSPORTATION

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Abstract

Over the last four decades, slurry pipelines have proven themselves to be a safe, reliable, and cost effective way to transport large tonnages of minerals over long distances. A variety of minerals have been successfully transported over distances ranging from a few kilometers (km) to 400 km. However, no long-distance bauxite pipelines have been built to date. Bauxite has developed a reputation for being difficult to hydraulically transport. This is about to change with the first long-distance slurry pipeline. The 250-km-long, 10 MT/y capacity pipeline was designed by PSI. Several other pipelines are currently being considered for transportation of bauxite. It will be shown that a properly designed hydrotransport system is an economically viable and reliable alternative for the long-distance transport of bauxite ore, as has been demonstrated for numerous other minerals. The focus of this paper is on how to integrate a pipeline into an existing facility.

1. Introduction

During the 1960's and 1970's a number of alumina refineries were built around the world, often near large deposits of bauxite in close to port facilities. After decades of mining, many of these nearby bauxite reserves are becoming depleted. In order to continue operation of existing refineries or, in some cases, to expand their capacity, new ore deposits farther away from the refineries will have to be exploited. Over the last 40 years slurry pipelines have moved from a status of being an intriguing, but rather risky possibility to it's present status as a cost-effective, highly reliable alternative to the conventional transportation modes. Most of the slurry pipelines transport material whose flow behavior does not change significantly during transport. Bauxite ore tends to generate fine particles (minus 45 microns) when sheared. The effective viscosity of slurry increases with an increase in fines in the slurry. Changes to the slurry viscosity during transport make any material more difficult to transport using slurry pipelines. The extent of the particle breakage and impact can be assessed such that the pipeline system can be designed to account for the change.

2. Design Considerations

2.1 Transportation System

The bauxite transportation system can be divided into slurry preparation, slurry pipeline system, and dewatering system. The bauxite ore is mined and washed to remove impurities. It is then crushed and ground to a size that is suitable for pipeline transportation. A source of water is needed at the mine to prepare slurry.

The prepared slurry is fed to slurry storage tanks that typically store about 8 hours of plant production providing a buffer between beneficiation and pipeline operations. The slurry from these tanks is fed to the slurry pipeline. Pumping facilities at the mine site, as well as at intermediate locations, may be needed to transport the slurry to the refinery. If the mine is located at a higher elevation compared to the refinery, then it may be possible to transport the slurry without using pumping facilities.

The slurry is delivered into slurry storage tanks near the refinery. The slurry will require dewatering prior to delivery to the refinery. Depending on the moisture content requirements of the filter cake, vacuum ceramic filters or pressure filters may be used to dewater the slurry. The filtrate is clarified and treated prior to disposal, or may be used as process water at the refinery. The clarified water can be recycled back to the mine if needed, substantially reducing the amount of fresh water required for preparing the slurry.

2.2 Pipeline Throughput

The pipeline throughput depends upon the refinery requirements. The operating availability of the mine, beneficiation plant, pipeline, and the dewatering plant can be different. Storage facilities are provided to accommodate differences in availability of different components.

2.3 Density of Solids

The following table presents the specific gravities of different mineral concentrate and tailings.

Table I: Typical Solids' Specific Gravity

Concentrate type	Specific Gravity of Solids
Iron	4.5 – 5.0
Copper	4.2 – 4.8
Zinc	4.0 – 4.3
Nickel Laterite	3.3 – 4.0
Phosphate	2.8 – 2.9
Bauxite	2.5 – 3.0
Coal	1.4 – 1.5
Gold Tailings	2.7 – 2.9
Copper Tailings	2.5 – 3.0

The specific gravity of bauxite solids is similar to that of sand. A solids specific gravity of 2.5 to 3.0 is normally encountered

2.4 Grind size

Typical bauxite ore is coarser than suitable for long-distance transport by pipeline — therefore, it must be ground finer than the typical process requirement to be transported in the pipeline. The optimum particle size distribution (PSD) for hydrotransport is a balance between: grinding, pumping, pipe steel, and thickening or filtering costs, as well as the impact on refinery operations. Within limits, the finer the grind, the easier it is to transport solids by pipeline. In particular, it can be transported at lower velocities without dragging a bed or sanding out. This reduces the pumping power required and the erosion rate of the pipeline. However, this comes at a price. Finer slurries tend to be transported at lower solids contents, increasing the volume to be transported and stored. The lower slurry velocity requires a larger diameter pipe for any given flow rate, and that may increase capital costs. A finer grind requires a larger mill and consumes more power and grinding media. Filtering becomes more difficult and more expensive as the particles get finer. Table II presents the typical PSDs for conventional slurry pipelines.

Table II: Typical Particle Size Distribution of Pipeline Slurry

Concentrate Type	% - 65 Mesh (210 μ)	% - 325 mesh (44 μ)
Iron	100	60 – 80
Copper	97 – 100	55 – 85
Zinc	100	60 – 80
Phosphate	65 – 85	35 – 50
Nickel Laterite	>95	60 - 90
Bauxite	95	40
Coal	50 – 60	20 – 30
Gold Tailings	100	60 – 80
Copper Tailings	70 – 90	30 – 50

2.5 Slurry Concentration

The slurry concentration should be as high as possible in order to reduce the amount of water transported with the solids. Slurry concentration is selected such that the friction loss in the pipe is not very high. For bauxite slurry the slurry concentration is expected to vary between 45, for fine slurry PSD, and 55 weight percent (wt%) solids for coarser slurry PSD.

2.6 Slurry Flow Rate

The slurry flow rate depends upon solids throughput, solids density, and slurry concentration. The mass flow rate of slurry is obtained by dividing the solids throughput by the slurry concentration in wt%. The mass flow rate of liquid (water) is obtained as a difference between the slurry mass flow rate and the solids mass flow rate. The volumetric flow rate of slurry is obtained by adding the volumetric flow rates of solids and water. The volumetric flow rate is obtained by dividing the mass flow rate by the density of the material. For example, if 5 million tons per year of bauxite solids are to be transported, and assuming an operating availability of 8322 hours per year, the hourly throughput of solids will be 600 tons per hour (tph). Assuming a slurry concentration of 50 wt% solids, the mass flow rate of slurry will be 1200 tph. Assuming a solids density of 2.65 tons/m^3, and a water density of 1 ton/m^3, the slurry flow rate will be 826 m^3/h.

2.7 Slurry Flow Properties

Bauxite slurry behaves like a Bingham plastic fluid. The flow behavior is defined by plastic viscosity and yield stress.

$$\tau = \tau_y + \eta\gamma \qquad (1)$$

Where: τ = shear stress, Pa
τ_y = yield stress, Pa
η = Plastic viscosity, Pa.s
γ = rate of shear, 1/s

The yield stress of slurry is a strong function of particle surface area. For a given volume of solids, particle surface area increases when the particle size is reduced. Bauxite slurry particles tend to break down and generate fines when subjected to shear. Thus the yield stress of slurry traveling via a long-distance pipeline can be significantly higher than that of a fresh slurry sample.

The particle attrition occurs by the breaking off of the edges of larger particles, creating very small size particles. These particles tend to form flocs that immobilize water and act like a part of the particle volume.

The friction loss in a pipeline depends upon the flow regime. In laminar flow regime, friction loss depends upon yield stress as well as plastic viscosity. In turbulent flow regime, the friction loss is governed by plastic viscosity.

3. Water supply

Most existing long-distance concentrate pipelines are operated as "open" systems. Recently, some slurry pipeline systems include a return water pipeline due to a water shortage at the mine site. Fresh water (or process water from the beneficiation plant) is used to dilute the concentrate. At the terminal, the dilution water and filtrate is separated from the concentrate and used in the downstream process or is treated and discharged into the environment. Because the concentrate (e.g., copper or zinc) is a small percentage of the whole ore tonnage, and the slurry is transported at a high concentration, the total amount of excess water is small. Treatment and discharge into the environment is the economic alternative.

Bauxite is transported as a whole ore, at high tonnage rates, and can only be transported in a pipeline at a relatively low solids concentration, so a large volume of liquid is required. As a result, installing an "open" system would require finding and obtaining rights to a reliable source of fresh water near the mining area. Wells and pump stations would need to be built, powered, and operated. The water would need to be pipelined to the pump station. Large water storage ponds would be needed at the mine to ensure a continuous supply.

At the refinery, only a portion of the dilution water could be used in the process without causing water balance problems. The current operation is balanced for the moist bauxite from the mine (i.e., 82% solids by weight) and a small amount of make-up. Any filtrate that cannot be used in the process would need to be treated for discharge into a nearby water body, or in ponds designed to store water. Alternately, the water could be used for irrigation in any agricultural/pasture areas surrounding the plant, which would also require treatment and a considerable amount of distribution piping.

Shorter tailings pipelines are usually "closed" systems. For example, red mud (slurry) from the refinery is sent to the tailings impoundment area and the decanted pond water is returned to the refinery. The need for treatment of the discharge water is eliminated, as is the need for most of the make-up water. Clarification of the filtrate is not required because the small percentage of ultra-fines returning to the mine will have a negligible impact on the pipeline operation.

3.1 Carrier Fluid Options

Once a system is closed, it is no longer necessary to dilute the solids in water. In the Bayer process, the bauxite ore is ground and slurried in spent liquor before being pumped to the digesters. This spent liquor could be delivered to the pipeline beneficiation plant at the new mine. The main advantage of this is that slurry coming out of the pipeline can be directly fed into the refinery with little or no dewatering required. Slurry diluted in water needs to be put through expensive filters to reach the high solids content required to maintain refinery water balance.

4 System Design

4.1 Velocity of Flow

A key design parameter in any slurry pipeline system is the operating velocity range. In a conventional (turbulent) system, the line velocity must be high enough to maintain turbulence and to prevent deposition of the coarse particles. However, if the operating velocity is too high, pressure losses and pipeline wear rates can become too high for the system to be economic.

For a long-distance, cross-country pipeline the minimum operating velocity should be higher than the laminar-turbulent transition velocity and the deposition velocity. Methods for determining these values are described in detail elsewhere [2]. In general, viscous slurries (i.e., ones with a higher solids concentration and/or fine particles) will be transition velocity limited. Dilute slurries, and/or coarse slurries, will be deposition velocity limited. As the solids concentration of any given slurry is increased, the transition velocity will increase and the deposition velocity will decrease. As a rule of thumb, the most economical concentration with which to run a long-distance pipeline is where the two values are equal.

The particle size distribution and slurry concentration are selected such that the deposition velocity and laminar turbulent transition velocity are less than 1.5 m/s. This allows the long-distance pipeline to be designed at a velocity in the range of 1.5 to 2 m/s.

4.2 Pipe Diameter

The pipe diameter is selected such that the desired velocity of flow is obtained at the design throughput.

4.3 Throughput Variation

Normally the refinery throughput may change over a range of throughputs. This can be accommodated to some extent by a change in flow rate, as well as by a change in slurry concentration. The pipelines are designed to operate within a narrow concentration, as well as a specific flow rate range. If the plant requirement drops below the minimum continuous throughput capacity of the pipeline, then the pipeline is operated in batch mode. In a batch mode operation, alternating batches of water and slurry are transported through the pipeline.

4.4 Pipeline route

A buried cross-country pipeline is normally used for long-distance transport. If a recycle water line is needed, it will also be buried and installed in the same right of way as the slurry line. Selection of the pipeline route must consider: system hydraulics, constructability, existing land usage, access rights, and future mining plans.

The primary issue with system hydraulics is to optimize capital costs (pipe diameter, pump size, etc.) and operating costs (the amount of pumping pressure/power required). In a flat area, this is relatively straightforward: keep the line as short as possible. In mountainous areas it becomes more complicated. Pressure requirements are primarily set by high points along the route. This may require extra pumps and pump stations, and include chokes after the high points to dissipate excess pressure on the downhill runs. The total cost of a system can be reduced substantially if high points are avoided, even if the total length is much longer than a straight line. Also of hydraulic concern are keeping the hydraulic profile line close to the ground to reduce operating pressure, and therefore, the required wall thickness of the pipes. The profile of the route will also affect the magnitude of transient pressures in the system, particularly when running water batches through a slurry line. These issues are described in detail elsewhere [1].

Constructability (including existing land usage and access rights) can strongly affect the overall costs of a pipeline. Rocky or swampy areas are hard to build in. Side hill cuts, river crossings (either under or over), and tunnels are expensive. Land acquisition in developed areas can be problematic. Pipelines can be, and have been, run through all of these areas, but it may be more economical to extend the pipeline to by-pass them. Having an experienced pipeline construction engineer involved in the route selection process is usually money well spent.

4.5 Pumping requirements

The pumping requirements depend upon the friction loss through the pipeline, as well as the static head required due to changes in elevation between the mine site and the refinery site.

Bauxite slurry is expected to flow as a homogeneous slurry. The friction loss of homogenous slurry mainly depends upon the viscosity, density, velocity of flow, pipe diameter, and pipe roughness.

4.6 Number of Pump Stations

In a long-distance pipeline the pumping pressure may be such that more than one pump station is needed. The total cost of the pipeline system is equal to the sum of the cost of pump stations and the pipe steel tonnage. The maximum pressure in the pipeline is reduced when more than one pump station is used. The pipe wall thickness requirement depends upon the pressure in the pipe. Therefore, the cost of pipe will decrease, but the cost of pump stations will increase with an increase in the number of pump stations. The selection of the number of pumps stations required depends upon an economic analysis using a various number of pump stations along the pipe.

4.7 Pipe Steel Requirements

The pipe wall thickness requirement depends upon the operating pressure in the pipeline. Long-distance pipelines normally use more than one wall thickness in order to reduce steel requirements. Slurry pipelines can be designed to have a maximum allowable stress equal to 80% of the specified minimum yield stress (SMYS) of the pipe steel. Pipe steel in various grades is available. Recently, pipes have been designed using pipe steel having a SMYS equal to 4827 MPa (70,000 psi).

The wall thickness computed, based on allowable operating pressure, should be increased to account for anticipated corrosion rate during the economic life of the pipeline.

Minimum pipe wall thickness depends upon the pipe diameter. If the wall thickness is too thin, it could give rise to handling problems during construction.

Maximum wall thickness should be limited based on the capability of the pipe mill, as well as welding considerations.

5 Major Equipment

Most mine operators are familiar with slurry preparation and dewatering equipment. However, the use of a slurry pipeline requires additional equipment that may not be familiar to many mine operators, and these are briefly discussed in this section.

5.1 Pumps

The discharge pressure, controls the basic decision of whether to use centrifugal pumps or positive-displacement (PD) pumps.

Centrifugal slurry pumps can handle large flow rates, but are limited to about 40 m head per pump. These pumps are less expensive and easy to maintain. When higher pumping heads are needed, the pumps can be arranged in series. Normally the maximum pumping pressure is limited to about 5 MPa (725 psi).

PD pumps havea limited flow capability (about 300 m^3/h) per pump, but can develop very high pressures. Pumps capable of producing 25 MPa (3650 psi) have been used in long-distance slurry pipelines. Pumps can be arranged in parallel to achieve higher flow rates.

For discharge pressures below 5 MPa (725 psi), a lower capital cost with installation of centrifugal pumps provides an economic advantage over PD pumps, especially when large flow rates are encountered. However, the total cost of a centrifugal pump system can sometimes be more expensive compared to PD pump system, as a spare line of pumps is needed as spares in order to achieve a high system availability.

Two types of impellers and liners are used for centrifugal slurry pumps. Wear-resistant, metal-lined pumps are used when handling coarse particles. Rubber-lined pumps are used when handling fine slurries.

The following types of PD pumps have been used for high-pressure pumping systems.

- Piston Pumps
- Plunger Pumps
- Piston-diaphragm Pumps
- Hydrohoist (Lock-hopper) Systems

The piston pump has a piston, which is driven by a crankshaft, and is in constant contact with the cylinder wall during each stroke. This action would result in high wear if the pump were used for pumping abrasive materials such as iron ore. A modified plunger pump was therefore introduced for such service. It has a plunger, which is continuously flushed with clear water during the suction stroke, thus greatly reducing internal wear.

The parts that most often experience wear in a piston pump system are: valves, valve seats, plunger or piston packing, plunger sleeves or cylinder liners, and brass bushings.

Piston-diaphragm pumps use a diaphragm that is pushed back and forth using a piston pump that pumps hydraulic fluid from a pump reservoir that is in closed loop. The only parts experiencing wear are valve, valve seats, and the diaphragm. This feature greatly reduces the maintenance of the pump. Piston-diaphragm pumps have been used for abrasive slurries with maximum pump pressures up to 25 MPa (3650 psi).

Pump flow rates and maximum discharge pressures are a function of the piston or plunger diameter, and power end horsepower capability. As the piston or plunger diameter increases, the flow rate increases and the maximum working pressure decreases.

PD pumps have a higher efficiency rating compared to centrifugal slurry pumps. PD pumps require more skilled maintenance labor than that of centrifugal slurry pumps.

A hydrohoist system consists of two or more pipes arranged in parallel. Slurry is fed into one of the pipe chambers by opening a valve to admit slurry in that pipe chamber. Each chamber has inlet valves for low-pressure slurry feed and high-pressure water feed. On the other end of the chamber, there are outlet valves to pump out slurry that is pressurized with high-pressure water, or to pump out water using low-pressure slurry. The pipe chambers are alternatively filled with slurry and pumped out, using water under high pressure, by synchronizing the opening and closing of valves.

6 Conclusions

Slurry pipelines have been successfully used for transporting different types of concentrates and other materials.

Bauxite ore can be economically transported using slurry pipelines.

For long-distance transport of bauxite, the ore will have to be more finely ground than for current refinery feed systems.

Bauxite particles tend to break up and generate fines that increase the yield stress of slurry. The pipeline system design should be based on the rheological properties of the bauxite slurry, allowing for expected attrition during pipeline transportation.

Bauxite slurry can be transported at a slurry concentration in the range of 45 to 55 wt% solids.

Positive-displacement pumps may be needed to develop the high pressures that might be needed for long-distance transportation.

7 References

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