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DESIGN AND OPERATION OF THE WORLD'S FIRST LONG DISTANCE BAUXITE SLURRY PIPELINE

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Abstract

Mineracão Bauxita Paragominas (MBP) is the first long distance slurry pipeline transporting bauxite slurry. Bauxite had developed a reputation for being difficult to hydraulically transport using long distance pipelines. This myth has now been proven wrong. The 245-km- long, 13.5 MTPY capacity MBP pipeline was designed and commissioned by PSI for CVRD. The pipeline is located in the State of Para, Brazil. The Miltonia bauxite mine is in a remote location with no other efficient means of transport. The bauxite slurry is delivered to Alunorte Alumina refinery located near Barcarena. This first of its kind pipeline required significant development work in order to assure technical and economic feasibility. This paper describes the technical aspects of design of the pipeline. It also summarizes the operating experience gained during the first year of operation.

1. Introduction

The world's first and the largest long distance bauxite slurry pipeline was put into operation this year. The Mineracão Bauxita Paragominas (MBP) pipeline was designed and commissioned by PSI for Companhia Vale do Rio Doce (CVRD). The ore is mined from Miltonia 3 area and is beneficiated and processed prior to transportation to the Alumina plant of Alunorte near Barcarena. The mine and the pipeline are located in the State of Para, Brazil as shown in Figure 1. The Miltonia bauxite mine is in a remote location with no other efficient means of transport. The expansion of the Alunorte alumina plant required additional sources of bauxite. Miltonia mine was in the vicinity and was found suitable for the Alumina plant.

Remote location and lack of other means of transport provided an incentive for considering pipeline transport. Since bauxite ore is normally delivered to the alumina plant in dry form, use of a slurry pipeline required use of dewatering facilities as a part of the transportation system.

Figure 1. Map of Brazil and Pipeline showing location of Mine and Alumina Plant

2. System Design.

2.1. Pipeline Throughput

The pipeline system was designed to transport an ultimate throughput of 12.59 dry million tonnes of dry bauxite ore. The slurry is dewatered to achieve a moisture content of 12%. The feed to the alumina plant with 12% moisture is 13.5 million tons per year (MTPY). During the first few years of operation the pipeline throughput is scheduled to increase in three stages. The initial capacity of the beneficiation plant is 4.5 MTPY. It will be increased to 9 MTPY after one year and then it will be increased to 13.5 MTPY after a few years.

2.2. Solids Particle Size

As noted before, the bauxite ore is ground to a size suitable for pipeline transport. The grind was selected such that slurry can be dewatered to 12% moisture at a reasonable cost. This required a particle size with about 6 percent plus 210 micron (65 mesh) and 40 to 47 percent minus 44 micron (325 mesh). The particle size is finer compared to that required for Alumina refinery.

2.3. Slurry Concentration

The slurry concentration should be kept as high as possible in order to reduce the amount of water transported. Certain minimum concentration is required to keep the solids in suspension. The slurry behaves like Bingham plastic fluid. The flow properties of a Bingham plastic fluid are defined by the plastic viscosity and yield stress. Both the plastic viscosity and yield stress of slurry increases with an increase in slurry concentration. An increase in viscosity and yield stress leads to an increase in laminar to turbulent transition velocity. Turbulent flow should be maintained in a long distance pipeline to keep the solids in suspension. Due to this reason, the maximum slurry concentration is selected such that the slurry yield stress is less than about 8 Pa.

2.4. For the selected size distribution, the slurry concentration range suitable for pipeline transport ranges is from 47 to 52 wt% solids.[1]Particle Breakage

Initial loop tests in CVRD laboratory had indicated that the ore particles break down and the slurry viscosity as well as yield stress increases with time. PSI had developed a laboratory test procedure to simulate particle break down with time of travel in the pipeline. A number of samples from various areas of the mine were tested for rheology with and without shearing to establish design basis for the pipeline. The shearing test involved agitation of a sample of slurry in a reaction vessel for 24 to 72 hours. The energy input to the slurry was approximately equal to the estimated pumping energy required for pipeline transport. These tests indicated that the plastic viscosity as well as yield stress of the slurry increased due to shearing. The impact of shearing was considered as a part of the design in establishing slurry concentration range.

In order to determine the extent of particle breakage in the actual pipeline, particle size analysis was carried out for product received in the tank, product following loop tests as well as the product received at the pipeline terminal. The slurry was kept in storage tanks with agitators for extended periods, prior to transport through the pipeline. Testing in the full size loop at Miltonia and during transport to the terminal demonstrated the bauxite slurry to be very stable; there was no evidence of particle attrition or batch breakdown. The plastic viscosity and yield stress remained unchanged.

2.5. Solids Specific Gravity

The solids specific gravity varies between 2.6 and 2.8.

2.6. Pipeline Flow Rate

The design flow rate for the pipeline was based on design throughput at an average design concentration of 50.5 wt% solids. The minimum flow rate was based on the minimum velocity to maintain turbulent flow and at the same time keep solids from settling. [2 3]. The pipeline flow rate range varies from 1680 to 2095 m^3/h.

2.7. Corrosion Control

The pipeline is externally coated and an impressed current cathodic protection system is used to prevent external corrosion. The processing requirements at the alumina refinery prevented use of corrosion control by chemical addition. No chemical additives are added for control of corrosion in the pipeline. Corrosion tests were carried out that indicated a corrosion rate of 0.2 mm per year (8 mpy) for the slurry. In order to obtain a 25-year design life of the pipeline, a corrosion allowance of 5 mm (0.2 inch) was added to the wall thickness needed to contain pipeline pressure.

2.8. Pipe Diameter

The pipe diameter was selected such that the design throughput can be transported at a velocity greater than the minimum velocity to prevent laminar flow as well as deposition in the pipeline. A pipe with 609.6 mm (24-inch) in outside diameter was selected to meet these requirements. For the initial throughputs of 4.5 and 9 MTPY, the beneficiation plant production will be less than the minimum continuous throughput requirement for the pipeline. In order to maintain flow of slurry in the pipeline, alternate batches of slurry and water were pumped.

2.9. Pumping Requirements

The pumping requirements depend upon the pipeline length and profile. The pipeline is 245 km long. Use of a single pump station would require very high pumping pressure and thicker wall steel pipe. Use of two pump stations for the design throughput of 13.5 MTPY was required. For the initial throughput of 4.5 MTPY only one pump station was necessary to transport the slurry-water batches. Therefore, only the mine site pump station was built for the initial throughput. When the pipeline throughput increases to 9 MTPY, the length of slurry batches increases and gives rise to 13.4 MPa pumping pressure.

The high internal corrosion rate required that a second pump station be installed after about 5 years to keep the operating pressures within allowable pressure for the pipeline. A second pump station will also be needed when the pipeline throughput increases to 13.5 MTPY.

Figure 2 shows the pipeline profile and hydraulic gradient for the initial throughput of 4.5 MTPY. Notice that after 5 years the allowable pressure near km 50 is close to the operating pressure due to corrosion metal loss. A second pump station is needed after 5 years of operation.

The pumping pressure at 4.5 MTPY throughput with one pump station was estimated to be 11 MPa. An 8 hour slurry batch followed by a 13 hour long water batch is pumped at the initial throughput. Both slurry and water batches are pumped at a flow rate of 1680 m^3/h.

Figure 3 shows the pipeline profile and hydraulic gradient for the design throughput using two pump stations. Slurry is continuously pumped at 1950 m^3/h at a concentration of 50.5 wt% solids. The pumping pressure at the first pump station is estimated to be 8.7 MPa at the first pump station and 11 MPa at the second pump station. The second pump station is located at about 116 km downstream of the first pump station.

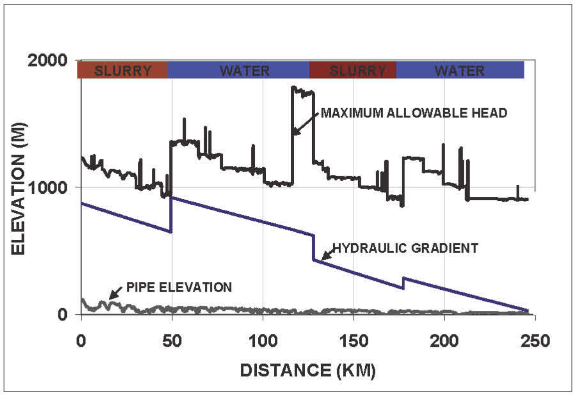

Figure 2. Pipeline Profile and Hydraulic Gradient at 4.5 MTPY Throughput.

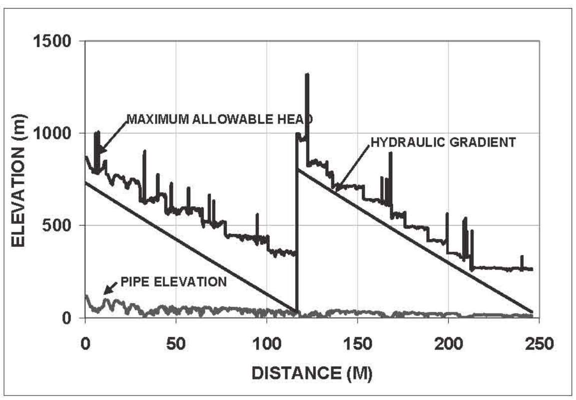

Figure 3. Hydraulic Gradient at Design Throughput.

3. Description of Facilities

3.1. Slurry Preparation

The bauxite transportation system can be divided into slurry preparation, slurry pipeline system, and dewatering system. The bauxite ore is mined and crushed using primary and secondary roll crushers to obtain a minus 153 mm product. Figure 4 shows the ore beneficiation plant and pipeline system flow sheet. The crushed ore is brought near the beneficiation plant by trucks and stacked for homogenization. The ore is reclaimed and fed to an open circuit semi autogenous (SAG) mill. The SAG mill product has 50 mm top size and is screened to separate plus 12.7 mm solids that are fed to a crusher and then to a closed circuit ball mill for further grinding. The minus 12.7 mm fraction from the screens is sent to cyclones. The particle size of the product is adjusted using cyclones and the product is thickened to 50 wt% solids.

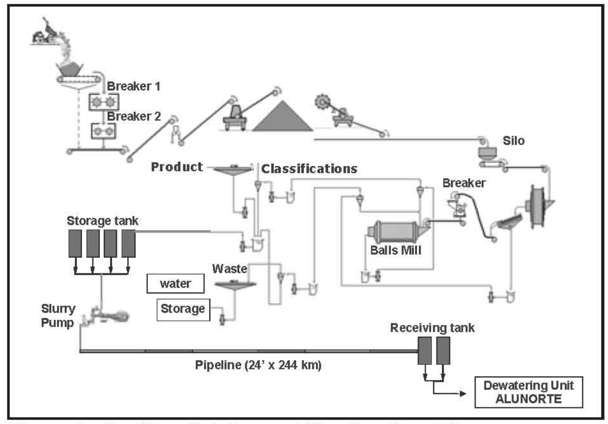

Figure 4. Ore Beneficiation and Pipeline flow Diagram.

The tailings are separated and sent to waste thickener. The slurry from the beneficiation plant is fed to the storage tanks at the mine site pump station.

3.2. Pipeline System

At the pump station, four 20 m diameter by 24 m high agitated slurry tanks feed two slurry charge pumps (one operating, one spare). The charge pumps provide the necessary suction pressure for six mainline piston diaphragm pumps (five operating, one spare). Each of the six GEHO TZPM 2000 mainline pumps is designed for a maximum flow rate of 356 m^3/h and a maximum discharge pressure of 13.7 MPa. These are the largest available slurry pumps worldwide, and six of these pumps in one location constitute the largest station ever built for a slurry pump station.

Figure 5. Photo of Pump Station.

The pipeline is 609.6 mm (24-inch) in outside diameter and is designed to carry bauxite concentrate, from an elevation of 120 Meters above Sea Level (masl) at the mine site at 25 masl at the pipeline Terminal at Barcarena. Figure 6 shows the pipeline route. The pipeline passes through tropical forests and is subject to flooding. It crosses four major rivers - Capim, Acara Mirim, Acara, and Moju. It also crosses PA-256, PA-451, PA-252 and PA-151 highways.

The pipeline shares right-of-way with two existing Kaolin slurry pipelines between tome Acu and Barcarena. The maximum pipe slope is limited to 15 percent in order to allow limited duration shutdown and restart of the pipeline with slurry in it.

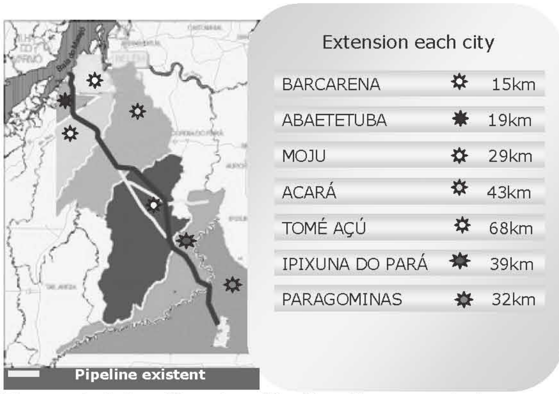

Figure 6. Map Showing Pipeline Route and the two Existing Kaolin slurry Pipelines.

The required motive force to overcome friction losses is provided initially by one main pump station located at Kilo Post (KP) 0 and a future intermediate booster station located at KP 116.4 when the throughput of the pipeline increases to its design value or when a corrosion metal loss of 1 mm has occurred. The second pump station will also have six piston diaphragm pumps having the same flow and pressure capability as at the first pump station.

The pipeline is designed in accordance with ASME B31.11 that allows maximum pipe stress of 80% of specified minimum yield strength (SMYS) of pipe steel. The pipe is made out of X70 steel having am SMYS of 482.76 MPa (70,000 psi). The pipe wall thickness is reduced along the pipe as the operating pressure in the pipe decreases. The wall thickness is selected based on calculate wall thickness required for maximum operating pressure plus the corrosion allowance. The pipe wall thickness varies between 7.9 mm and 15.9 mm (0.312 and 0.625 inches).

The pipeline system is designed with a leak detection system and five intermediate pressure monitoring stations (PMS) at approximately 40-km intervals to provide constant pipeline pressure data to the pipeline operator. The pressure data is transmitted using a fiber optic cable system. The PMS stations as well as the fiber optic system have not been completed, and voice communication between the pump station and the pipeline terminal is used at the present.

Pressure Measuring Station	Location (km)
PMS1	43.8
PMS2	85.4
PMS3	167.9
PMS4	206.3
PMS5	116.4

At the terminal station, three 20 m diameter by 24 m high agitated slurry tanks, two of which provide holding capacity to feed the filter plant and the remainder is used as "trail-out" tank. The trail out tank is to feed a clarifier/thickener with 3% to 6% solids. The main objective of this is to clarify the "dirty water" to achieve a solids content below 120 ppm. The clarifier/thickener underflow is recycled to the slurry holding tanks.

The slurry is dewatered using hyperbaric pressure filters to produce a bauxite with about 12% moisture. The filtered bauxite is used by Alunorte to produce alumina.

4. Pipeline Operation

During the first few years of operation, the pipeline is expected to operate in batch mode. The pipeline production is to ramp up from 4.5 MTPY in year 1, then to 9 MTPY in year 2 and ultimately to 13.5 MTPY after 5 years.

The pipeline is controlled by an operator located in the pump station control room at Miltonia. The pipeline operates continuously being fed with bauxite slurry at a concentration of about 50% solids from the agitated slurry tanks at Miltonia. The four slurry tanks are designed to hold about 6700 m^3 of slurry each, and in the early years of operation, the pipeline will drain the tanks faster than they can be filled by the beneficiation plant. When the tanks are drawn down to a low value, the pipeline operation switches to water from slurry to maintain the flow of slurry in the pipeline at all times.

As the output of the beneficiation plant grows with each of two planned expansion cycles, the volume received by the tanks will increase so that the pipeline will be able to transport slurry continuously.

Slurry quality is monitored continuously. Slurry characteristics including rheology, density, and particle size distribution are determined prior to each batch being admitted to the pipeline. If any slurry properties fall outside the minimum specification required for transportation the slurry is adjusted to achieve minimum requirement prior to shipment. A full laboratory is maintained by CVRD at Miltonia, and every batch is tested and approved for transport in the pipeline.

The pipeline operator at Miltonia remains in contact with the terminal so that the departure and arrival time and location of each slurry batch is known. As noted earlier, the fiber optic telecommunication system has not yet been installed and therefore voice communication is required. The terminal operation therefore has an estimated arrival time for each batch, and is ready to receive slurry when it arrives. Each slurry batch takes approximately 40 hours to travel the 245 km pipeline, so this requires close coordination between operations at both ends of the pipeline. Ultimately, the end user, (the filter plant at Barcarena) has control of the volume being shipped in the pipeline, since they must have storage space available for the slurry once it has been admitted to the pipeline. Following the installation of the communications system and PMS stations, the Pipeline AdvisorTM (PSI's proprietary expert pipeline monitoring software) will be able to monitor the batch locations in the pipeline.

The pipeline is controlled by the operator using a series of programmed operating sequences that have been written and checked out during commissioning. Many of these sequences are automated and are available to the operator at the touch of a button. Some sequences are performed manually to permit the operator to fully supervise them, but as the operation gains maturity, most will be become automated.

The pipeline operates continuously at a constant flow rate, and the slurry is not shut down in the line for any reason other than an operating emergency. This can arise from loss of power or loss of pumps at the station for example. In this case the pump station and pipeline is shutdown with slurry in the pipeline and the valve closed at the terminal. Once power has been restored, or pumps brought back into service, the pipeline is restarted on water to bring the slurry from a rest position in the pipeline to full operating speed in a carefully controlled sequence of operations. As noted earlier, the maximum pipeline slope is limited to 15 percent, which allows shutdown and restart of slurry batches in the pipeline without problems.

5. Commissioning

The pipeline system was commissioned from October 2006 through to May 2007. The commissioning effort followed a detailed program of tests on all equipment using water and then slurry to ensure that it performed according to specification and that it met the design requirements for the system.

This included testing of agitated slurry storage tanks, charge pumps, mainline pumps, valves, as well as instrumentation, control systems, and the operator workstation system.

The slurry was extensively tested to ensure that the hydraulic properties met the design assumptions. A test loop constructed at Miltonia consisted of 300 m of line pipe having the same diameter as the mainline pipe to simulate the pipeline under controlled conditions. Slurry was circulated in this loop and properties measured to ensure compliance with system requirements. Slurry characteristics were measured in the test loop over a range of slurry variables to establish limits on those variables. Special attention was given to this work since this was the first bauxite pipeline to be commissioned in the world, with no previous commercial bauxite experience available as a guide.

Slurry batches were prepared and shipped to the port terminal under controlled pumping conditions so that pipeline equipment and system operation could be closely monitored and checked against design requirements.

Controlled system tests included system shutdown and restart with slurry in the pipeline to confirm these procedures and to train the operators.

Mainline pump operation and performance was checked, and pump maintenance procedures were put in place through on-the–job training following classroom work.

During commissioning some problems were encountered. This included excessive vibration of the pump discharge piping, lack of agitation at the top of the tank when it was filled above 19 m level, and locking of pump dampeners. These problems were carefully examined and successfully resolved.

Operations and maintenance assistance was provided to CVRD by PSI after the completion of formal commissioning activities to allow time for further review and refinement of the lessons learned during commissioning, and to reinforce the confidence of the operations team in running the newly commissioned pump station and pipeline facilities.

6. Operating Experience

Since the start of pipeline operations in May 2007, the system has operated well, and has achieved target production requirements with a high availability. The objective of the pipeline system is to have a higher availability than either the beneficiation plant or the filter plant. In this manner, the pipeline never impacts production or filtering throughput; so far this objective has been met. The production at the first pump station (EB1) from the start to the month of August 2007 is shown in Figure 7.

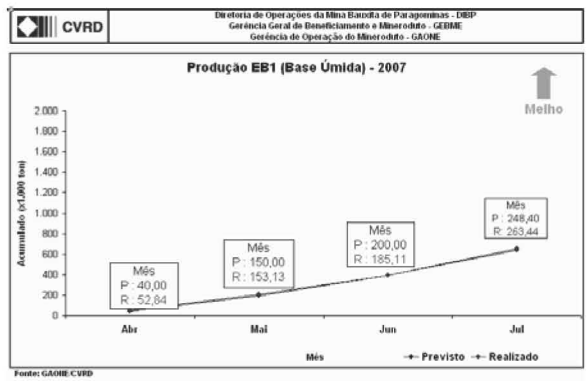

Figure 7. Bauxite ore slurry delivered through July 2007.

The pipeline has operated without any problems. The beneficiation process needs some fine tuning in order to meet the particle size requirements. The corrosion metal loss data using ultrasonic wall thickness measurements will have to be closely monitored to achieve the desired pipeline life. The slurry pressure loss characteristics have been found to be within the design estimates. As noted earlier, the attrition or increase in slurry viscosity and yield stress due to pipeline transport is not evident. The attrition observed during laboratory simulation tests may be due to the use of total slurry friction loss instead of the incremental friction loss due to the presence of solids in the simulations.

7. Conclusions

The project has shown that bauxite can be safely transported from mine to port in a large diameter, long distance slurry pipeline system.

This is the first of a kind, and represents a new chapter in the 50 year history of commercial slurry pipelining.

The operating data indicates that some of the concerns regarding particle break down and change in slurry rheology during transport have not been observed thus far.

The ore properties will likely change from one location to the other and therefore the absence of attrition cannot be assumed to hold true for all ore types. Additional experience from this pipeline will be very useful for the design of other bauxite ore pipelines.

The operating experience validates the design methodology and provides a valuable commercially proven benchmark against which other systems can be built.

Lessons learned from the operation of very large high-pressure pump stations are being applied to other projects with all types of slurries.

Opportunities to more fully integrate the pipeline and dewatering with upstream (beneficiation) and downstream (refinery) facilities are evident and can be applied in future projects.

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