LONG-DISTANCE TRANSPORT OF BAUXITE SLURRY BY PIPELINE

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Abstract—*The traditional methods of transporting bauxite from mine to alumina refinery over long distances are by rail or conveyor. However, slurrying bauxite and pumping it through a pipeline is a viable option that warrants serious consideration. This is especially true in rugged terrain where rail and conveyor construction can become expensive and time consuming. Furthermore, a pipeline can offer the benefits of being unobtrusive, more environmentally friendly, and less subject to interference from local populations. The world's first long-distance bauxite slurry pipeline was commissioned in Brazil in May 2007. Owned by Mineração Bauxita Paragominas (MBP), it is pumping up to 4.5 million tonnes of dry bauxite per year 245 km to the Alunorte Refinery. This paper discusses the advantages and disadvantages of a bauxite slurry pipeline and notes major issues in considering such an option. It compares the costs of the rail and pipeline transport options over a range of long distances traversing rugged terrain and identifies the point where economics begin to favor the pipeline.*

Keywords—*bauxite, breakeven point, economic pipeline length, long-distance pumping, pipeline, rail, slurry*

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INTRODUCTION

The traditional methods of transporting bauxite from mine to alumina refinery over long distances are by rail or conveyor. Bauxite is delivered to the refinery relatively dry as run of mine ore ready for feed into the plant crushing/grinding circuit.

However, an alternative means of transport gaining attention is to prepare a slurry from the bauxite ore at the mine and pump it through a pipeline to the refinery, where it is dewatered in high-pressure filters. This option warrants consideration when traversing rugged terrain where rail and conveyor construction can become expensive and time consuming. Furthermore, a pipeline can offer the benefits of being unobtrusive, more environmentally friendly, and less likely to suffer interference from local populations.

This paper discusses the advantages and disadvantages of the rail and pipeline transport options. The shorter-haul options of truck and conveyor are also discussed but discounted as not appropriate for long-distance transportation. The paper's focus is on the pipeline transport option and when this option is likely to become feasible in terms of cost and operation. Major factors requiring consideration when evaluating the pipeline option are outlined.

Costs are compared for rail versus pipeline, showing unit costs against distance. A cost breakeven point (BEP) is established to show under what conditions and over what distance pipeline becomes more cost-effective than rail.

BACKGROUND

Transporting minerals by pumping slurry through a pipeline has a perceived advantage throughout the transport system. However, many important issues need to be addressed when assessing a pipeline option.

Pipeline transport of minerals became of interest in 1967 after Bechtel constructed the world's first iron ore slurry pipeline: the 85-km-long Savage River project in Tasmania. Since then, long-distance slurry pipeline transport has become quite commonly adopted for mineral concentrates.

Interest has increased in the alumina industry, where the world's first long-distance bauxite slurry pipeline was commissioned in Brazil in September 2007. Owned by Mineração Bauxita Paragominas (MBP) and 245 km long, the pipeline is used to pump up to 4.5 million tonnes (dry weight) of bauxite per year across remote and rugged terrain to the Alunorte Refinery. [1]

ABBREVIATIONS, ACRONYMS, AND TERMS

BEP	breakeven point
MBP	Mineração Bauxita Paragominas
MPa	megapascal
Mt/y	million tonnes per year
w/w	weight-to-weight
µm	micrometer (micron)

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TRANSPORT SYSTEM OPTIONS

Options used to transport bauxite vary according to a number of factors, particularly distance and terrain. Transport options include short-haul truck, long-haul truck, overland conveyor, rail, and pipeline.

The two truck options are generally best suited for relatively short distances (up to 75 km) between mine and refinery. As distance between mine and refinery increases, the more-permanent overland conveyor, rail, and pipeline transport modes are generally employed to reduce the operating costs of hauling to the refinery. These three options require the establishment of mining and ore preparation hubs at each system's feed end; these hubs are typically fed from the mine face by short-haul trucks.

Each of the five options is briefly discussed in this section.

Short-Haul Truck

Large-capacity trucks (generally ranging from 100–250 tonnes) are cost-effective for hauls up to 20 km. They allow operational flexibility when mining occurs from multiple pits. They require costly heavy-duty haul roads (due to their high axle loads and width) that require ongoing maintenance to achieve optimum operations. Road costs are heavily affected by the terrain, rising rapidly as it steepens and as the roads are lengthened to maintain safe design parameters.

Long-Haul Truck

Specially designed large-capacity road-train trucks (generally ranging from 250–350 tonnes) increase the cost-effective haul distance to 50–75 km, depending on the terrain. They are designed to carry run-of-mine ore and can be loaded directly at the mine face. These trucks also allow mining from multiple facings while allowing a larger incremental extension of the haul distance. The haul roads are less costly than those for short-haul trucks because multiple axles reduce pavement load, but they are similarly affected by terrain.

Overland Conveyor

Overland conveyor systems are specifically designed to transport large quantities of bauxite and are cost-effective over distances of 15–100 km. A conveyor can have a single flight of 15–50 km, depending on the type chosen (e.g., cable belts). Longer distances require several conveyors in series. Conveyors occupy a smaller footprint than haul roads and accommodate steeper grades of up to 10%. They have horizontal alignment restrictions but can accommodate horizontal curves ranging from 2–4 km radius, depending on the tonnage being transported. Conveyor costs are affected by terrain, but the conveyors can be elevated in steel galleries to maintain the required vertical grades at creek or other crossings.

Rail

Rail is feasible for transport distances exceeding 100 km and excels in gentle terrain with only few stream crossings. Rail requires a generally flat vertical alignment with about 1% maximum grade. Horizontal alignment can accommodate tight bends down to 300 m radius. Rail is severely affected by terrain because it must follow the contours to maintain the low maximum grade and minimize cuttings. Therefore, in rugged terrain, rail length can become up to 50% longer than the length of a direct route unless large cuttings and embankments are constructed, with associated high costs. Stream crossings are usually expensive, requiring bridges and/or large culvert structures to accommodate high axle loads and flood flows.

Pipeline

A pipeline uses water as the transport medium, in contrast to the four dry options just described. The ore must be slurried with water to approximately 50% solids for pumping and then dewatered at the refinery to return it to the required moisture content for refinery feed. Because of this additional requirement, a pipeline becomes cost-effective only when long routes are being considered—usually well in excess of 100 km in rugged terrain. Slurry pipeline alignments, both vertical and horizontal, are considerably more flexible than those of rail or conveyor. Horizontally, pipe may weave around obstacles with a minimum radius of just a few meters. Vertically, pipe may rise and fall with grades of up to about 16%, which is a limiting factor to prevent settled particles from sliding downward when flow ceases. Pipelines are generally buried and follow existing terrain without substantial cut and fill earthworks. At creek crossings, the pipe is usually buried under the creek bed. Substantial rivers are crossed in conjunction with an access bridge.

TRANSPORT SYSTEM COMPONENTS

Overview

To further understand the different options, the entire transport system needs to be considered; that is, from mine face to refinery grinding circuit. This approach properly represents the total cost of a system on an equitable basis.

Table 1 shows the key components of each transport system, highlighting the fixed components (F) required for each transport mode, which is variable (V). Also highlighted are the components common (C) to all systems regardless of transport system.

The information in Table 1 indicates that the pipeline option has substantially more fixed components than the other options because of its slurrying and dewatering requirements. Thus, pipelines are feasible only for transporting bauxite over long distances, where these costs can be amortized.

The remainder of this paper discusses only the two long-distance transport options of rail and pipeline. To make this discussion meaningful, a better understanding is required of the features of each system. Therefore, the following paragraphs provide more detailed information about their key features.

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Rail

Rail is a straightforward, well-understood, bulk materials transport system. Robust in construction and operation, it offers great flexibility in its carrying capacity. Furthermore, it does not require altering the properties of the bauxite that feeds the refinery.

As described in Table 1, the rail system consists of a rail loading facility, the rail line, and a rail unloading facility. The requirement for loading and unloading facilities is independent of the transport length and so represents a fixed cost. The most significant variables affecting the cost of rail are transport distance, associated terrain, and number of significant crossings. Also, adverse geotechnical conditions such as hard rock in cuttings and access through swamps can significantly affect cost.

Table 1. System Components for Each Transport Mode

MATERIAL FLOW →									
Short-Haul Truck				Mine Supply (C)	Short-Haul Road (V)	Ore Crushing (C)	Storage (C)	Grinding (C)	Refinery Process (C)
Long-Haul Trucks				Mine Supply (C)	Long-Haul Road (V)	Ore Crushing (C)	Storage (C)	Grinding (C)	Refinery Process (C)
Overland Conveyor				Mine Supply (C)	Ore Crushing (C)	Overland Conveyor (V)	Storage (C)	Grinding (C)	Refinery Process (C)
Rail		Mine Supply (C)	Ore Crushing (C)	Rail Loading Station (F)	Rail Line (V)	Rail Unloading Station, Conveying (F)	Storage (C)	Grinding (C)	Refinery Process (C)
Pipeline	Mine Supply (C)	Ore Crushing (C)	Grinding (C)	Cycloning, Slurry Storage, Pumping (F)	Pipeline (V)	Slurry Storage, Dewatering, Water Disposal, Conveying, Power (F)	Solids Storage (F)	Re-slurry (F)	Refinery Process (C)

- Mine Supply = truck loading and local hauling
- Ore Crushing = truck dump, crushing, and local conveying

In rugged terrain, rail length can become up to 50% longer than the length of a direct route as the route follows contours to maintain the low maximum grade and minimize cuttings. If a more direct route is required, large cuttings and embankments must be constructed, with associated high costs. Stream crossings are usually expensive, necessitating bridges and/or large culvert structures to accommodate high axle loads.

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Rail system capacity is generally limited by the amount of rolling stock (wagons and locomotives) available. Typically, the smallest amount of rolling stock practicable is employed because rail requires such a large initial investment in rail loading and unloading facilities and formation earthworks. System capacity can be expanded only by incurring the expense of adding more rolling stock.

Rail does create a small barrier across the landscape, but pedestrian and/or vehicle access can be provided relatively easily and safely, commonly via large box-culvert access ways or crossover bridges.

Pipeline

The significant difference in transport via slurry pipeline is that the bauxite must be slurried for pumping and then dewatered to the equivalent moisture (12%–14%) found in the as-mined bauxite, before it is fed into the refinery. Dewatering is necessary because once the bauxite is in the refinery circuit, additional water content beyond the normal range incurs additional capital and power costs to evaporate the excess moisture.

As indicated in Table 1, the pipeline system has three major parts: slurry preparation facility, pipeline and pumps, and dewatering facility. Slurry preparation and dewatering are generally independent of pipeline length.

Slurry Preparation Facility

The slurry preparation facility includes crushing, grinding, water supply, agitator tanks, and slimes removal. To ensure that slurry pumping is performed as designed, a consistent product with the right characteristics must be fed into the pipeline. Achieving the correct particle size distribution during slurry preparation requires a well designed and controlled plant. The ideal particle distribution for bauxite slurry has a top size of 250 µm, with about 50% of the particles less than 45 µm. [1] Grinding circuits are generally designed to target this grading, but the ore feed from mining also plays an important role. It may be necessary to extensively practice and optimize the selective mining and blending of ores, because this part of the process affects the sizing of the end product considerably.

Pipeline and Pumps

The transport system from slurry preparation area to refinery consists of a long steel pipeline and high-pressure pumps, plus ancillary items. To pump large quantities of bauxite requires special considerations to maintain a high level of reliability in this single "life line." Of paramount importance are the characteristics of the bauxite particles in the slurry. Solids degradation by particle attrition through the pumps and pipeline could change the fluid rheology, which, in turn, could affect pumping by necessitating a higher hydraulic head and more power. Opportunities for the occurrence of plugs and leaks need to be mitigated by a design that reduces the risk of such events. The design must also maintain a pipeline velocity high enough to prevent solids from dragging on the bottom of the pipe in a situation called "incipient sanding," which can increase pipe wear, reduce pipeline life, and lead to a higher pumping head requirement as a result of the reduced flow cross-section.

Dewatering Facility

Once the slurry arrives at the refinery, significant processing is required to dewater it to about 12%–14% water content. This process minimizes the dilution of the refinery liquor in the circuit. Dewatering is typically achieved via a bank of hyperbaric high-pressure filters. [2] The filtration process uses large amounts of compressed air, and some processes use pressurized steam. The amount of power required to operate the filters and compressors and to produce steam is significant, typically about 12 MW for a refinery of 3.5 million tonnes of annual alumina capacity. Water from the filters is usually clarified before its release downstream. In some cases, it may be returned to the mine via a water pipeline, but this latter option is not normally practiced because of its high cost. The refinery also uses some of the water.

Expansion

The capacity of a pipeline and any expansion requirements must be decided upon during the initial design and construction phase because there is little opportunity to do so later. Sizing the pipeline only for the initial bauxite demand leaves little leeway to increase capacity. Additional pump capacity may produce only an extra 10%–20% of tonnage. To allow for additional future demand, the pipeline must be oversized until that demand is met. This means that batch pumping is required, which is operationally expensive because significantly more water than ore is delivered to the refinery. If the maximum future bauxite demand is met early, this could be an acceptable option because the high operating cost associated with pumping large quantities of water is limited in time.

COMPARISON OF RAIL AND PIPELINE SYSTEMS

Table 2 compares the attributes and differences of the rail and pipeline long-distance transport systems.

Many factors may make a pipeline more favorable. For example, if a transport site is long, located in rugged terrain, has safety and security concerns, and/or is located in environmentally sensitive areas or crosses numerous creeks, then the case for pipeline could be strong.

PIPELINE SYSTEM DESIGN CONSIDERATIONS

This section presents an overview of the key elements to be considered when designing a pipeline transport system. These elements are focused on water supply, slurry properties, and pipeline design.

Water Supply

A reliable water supply is essential. The water resource should be located near the slurry preparation area, with continuous supply to meet the demand. The water supply scheme generally involves an off-take weir from a local stream, with a pump station and a pipeline to a storage dam. The storage dam is needed to accommodate seasonal variations in stream flow. A pump transfers water to the grinding circuit for slurry preparation.

If water resources are scarce, a return water pipeline may be necessary from the dewatering facility at the refinery back to the mine, at increased project cost.

Providing a large diameter pipeline for future use initially means pumping significant extra quantities of water to the refinery.

Table 2. Comparison of Rail and Pipeline Attributes and Differences

SELECTION FACTOR	RAIL	PIPELINE
Distance	• Suited to 100+ km • Cut and fill quantities important	• Suited to 100+ km • Potentially higher cost BEP
Constructability – Rugged Terrain	• Heavy equipment for sleeper plant (in country), track, and bridge construction • High earthworks	• Pipeline simpler to construct, with minimal earthworks
River Crossings	• High cost for bridges and culverts	• Stream crossings simpler and cheaper (buried under stream bed)
Water Requirements	• Minor	• Water supply required for slurry preparation
Future Expansion	• Additional rolling stock • Sidings	• No expansion unless initially undersized or designed as batch transfer • Large diameter for future use means significant extra quantities of water
Security and Interference	• Exposed to risk from human and environmental influences	• Better protected and thus more secure because buried
Safety – Local Population	• Exposure to moving equipment	• Bauxite is enclosed in buried pipeline
Environmental – Habitats	• Can restrict fauna movement	• Low impact – Lower requirement for clearing because footprint is small • Habitat not cut off or isolated
Environmental – Noise and Dust	• Moderate to high impact	• Low impact – No noise or dust issues except during construction
Community – Impact of Route	• High impact • Larger deviations result in longer route	• Low impact – Can deviate easily • Fewer resettlement issues

Slurry Properties

- ***Rheology***—The rheology of the slurry influences a number of important factors in long-distance pumping. It is important to have sufficient slurry viscosity to prevent solids from settling out during short flow interruptions. To obtain the proper viscosity, the slurry must have a sufficient proportion of ultra-fine (less than 10 µm) particles. However, while the presence of these particles serves to increase slurry viscosity, it also increases pumping costs because of the increased head requirement. During normal flow, pipeline velocity must be above the minimum settling velocity to prevent larger particles from dragging on the bottom of the pipeline. The design velocity is usually above laminar flow, just inside the turbulent flow region. This compromise keeps particles in suspension and the pumping head as low as possible. A higher velocity may be used in the design to ensure that no particles settle even if larger particles appear due to change of grind or ore body. Pump test loops are used to confirm the hydraulic properties of the slurry before finalizing design.
- ***Slurry density***—The higher the slurry density, the better, from a transport viewpoint. Typically, 50% solids weight-to-weight (w/w) is used, but a higher density results in less water being transported. Water is the carrying medium only and is otherwise of no value. However, increasing pumping density beyond 55% increases pumping requirements in terms of both head and power. Higher concentrations have not been accepted for long-distance pumping because the operational risk element is too high at present.
- ***Grading***—The slurry grading is very important in achieving the right performance during slurry pumping. For bauxite slurry, the ideal grading has a top size of 250 µm, with about 50% less than 45 µm. A percentage of ultra-fine particles is desirable to improve slurry characteristics. However, if desliming is required to remove highly reactive silica, this may not be achieved. In this case, higher velocity pumping is required to keep the coarser particles in suspension.
- ***Particle degradation***—Much has been reported about the potential of bauxite to break down because the ore tends to be soft and could suffer particle size degradation due to turbulent flow and the mechanical impacts of pumping. Such a breakdown can increase the viscosity and the pumping head required. This is especially true if the proportion of ultra-fine particles is increased. However, MBP in Brazil has reported no particle attrition or increase in viscosity in more than 12 months since the initial operation of its bauxite slurry pipeline. [1]

The slurry grading is very important in achieving the right performance during slurry pumping.

Pipeline Design

Performance and Security Considerations

A pipeline's long-term performance and security are paramount for a successful slurry transport system. The following relevant concerns in determining pipe wall thickness require serious attention:

- ***Wear***—Erosion of the inside surface of the pipe is inevitable when a mineral slurry is being pumped. To deal with this issue, the pipe is either lined or provided with additional (sacrificial) wall thickness. However, experience has shown that bauxite slurry is not very abrasive and causes negligible erosion. Furthermore, most of the solids are in suspension because of the fine particles.
- ***Corrosion***—Interior corrosion is difficult to predict but must be allowed for if no lining is used. An allowance for bauxite is typically 0.2 mm/year. [1] The outside of the pipe is protected using a cathodic protection system coupled with a commercial paint system.
- ***Transients***—Pressure waves or transients are induced by velocity changes inside the pipeline. Sudden loss of power, valve closure, and column separation induce transients. In long pipelines, this can be significant and must be assessed. Slurry behaves differently from water, but there are occasions when the line is filled with water or only partially filled with slurry.
- ***Steel grade***—Higher grade steel yields a lower wall thickness, per hoop stress calculations. The availability of various grades and their costs affect the choice.

Pumping and Size Considerations

Pumping high-pressure slurry over long distances in a pipeline requires a number of serious considerations in the design process:

- ***Pumps***—The pumps used to drive the slurry along the pipeline must be robust, reliable, and of proven performance. For long pipelines, the selection of choice is the positive-displacement pump. Whereas centrifugal pumps are limited by the maximum casing pressure, typically about 7 MPa or 700 m head, positive-displacement pumps can provide pressures up to 25 MPa. Piston wear, once a problem, has been addressed by the piston diaphragm pump, in which a diaphragm protects the piston and liner from abrasive sliding contact wear.

- ***Pipeline internal diameter***—The pipeline internal diameter is crucial for the long-term performance of the system. A diameter should be used that achieves the minimum slurry velocity needed to prevent solids settling. This usually results in flow in the turbulent region. The penalty for using a smaller diameter and higher line velocity is higher pumping heads. However, this lower-risk strategy also decreases wear and reduces the chance of plugging.
- ***Valves and fittings***—A number of fittings are required for pipeline operation. These include isolating valves, scour valves, and air valves. Also, pressure monitors and magnetic flow recorders are installed as part of the monitoring/leak detection system. Air valves and scour valves facilitate emptying sections of pipeline and capturing the associated slurry in dump ponds. If these valves are not provided, managing line breaks or blockages could be challenging, particularly in very long pipelines.
- ***Dump ponds***—Dump ponds may be needed to trap and contain slurry if it becomes necessary to manage breaks and line blockages. The requirement to contain slurry depends on the environmental regulations of the country of operation.
- ***Power and controls***—Power supply and distribution are required, along with a feed control system. Commonly, a power distribution system of about 15 MW is required to deliver power to the pumps. A complex control system is required to link feed into the pipeline with demand at the refinery end. In addition, some long pipelines require leak detection monitoring, which involves recording slurry pressure at intervals along the pipeline and sending this information to the control room.

RISKS IN A PIPELINE TRANSPORT SYSTEM

A number of risks need to be addressed in adopting a pipeline slurry transport system. These are increased hydraulic pressure, shortened pipeline life, plugging, excessive slimes, and dewatering plant startup.

Increased Hydraulic Pressure

A change in slurry rheology as a result of altered particle size distribution changes the pump head requirements. For positive-displacement pumps, this means applying more power to the piston stoke and consequently drawing more power from the motor. To cover this possibility, a larger motor may be required.

Shortened Pipeline Life

The pipeline may be subject to greater wear if larger particles are generated in the grinding circuit due to a change in ore characteristics. Larger particles may drag as a shifting bed, thereby increasing erosion. In addition, a change in slurry chemistry may accelerate corrosion. Pipe inspections are needed to determine the extent of wall thickness reduction.

The pipeline internal diameter is crucial for the long-term performance of the system.

Plugging

The slurry should be within the design grading, with a top size of 250 µm and about 50% at less than 45 µm. With this grading and a pipeline slope of no greater than 16%, the risk of plugging is low. However, if there is a change in sizing, plugging is possible, especially if the pumps stop for more than 30 minutes.

Excessive Slimes

Slimes are detrimental to dewatering plant filter operation because they blind the filter cloths. Failure to remove slimes at the slurry preparation area increases filter usage and maintenance. This situation could be costly in terms of additional capital costs and lost refinery production.

Dewatering Plant Startup

It is possible that dewatering plant startup and commissioning could take at least 3 months. [3] Efficient plant operation may be further delayed if the initial slurry particle size distribution is too fine and/or there is a significant presence of slimes. Thus, control of particle size and slimes at the slurry preparation end is important from the outset of operations.

TRANSPORT SYSTEM ECONOMICS: RAIL VERSUS PIPELINE

Bauxite transportation system study data comparing rail and pipeline provides a range of costs for projects in a number of countries. The data covers rugged terrain sites in Cameroon, Guinea, Brazil, and Vietnam for production rates of 10 million tonnes per year (Mt/y) and 20 Mt/y.

Studies have shown that pipeline transport often does not become economical until transport distances of a few hundred kilometers are reached.

Table 3. System Components — Rail versus Pipeline

RAIL	PIPELINE
Land Acquisition – easements for rail	Raw Water System – pipeline, pump, and pond
Earthworks – cuttings, embankments	Slurry Thickener and Slurry Tank with Agitator
Stream Crossings – culverts, bridges	Slurry Pipeline
Trackwork – rail and rolling stock	Slurry Pumps – two pump stations
Signaling and Telecommunications	Slurry Tank with Agitator
Workshops – maintenance facilities	Pressure Filters
Crossings – level or grade separation	Water Clarifier (from pressure filters)

Table 4. Bauxite Rail and Pipeline Transportation Costs, 2006 (US$/Tonne)

BAUXITE TONNAGE AND DISTANCE		10 Mt/y			20 Mt/y		
		200 km	400 km	800 km	200 km	400 km	800 km
RAIL	Cameroon	3.37	6.60	12.06	2.41	4.57	8.72
	Guinea	3.83	7.08	13.77	2.90	5.45	10.54
	Brazil	4.08	7.17	13.48	2.85	5.30	10.06
	Vietnam	3.04	4.86	10.72	2.21	4.24	8.06
PIPELINE	Cameroon	5.75	7.55	10.97	4.77	5.82	7.91
	Guinea	5.74	7.51	10.87	4.76	5.80	7.49
	Brazil	5.47	7.32	10.74	4.51	5.57	7.62
	Vietnam	4.27	5.80	8.71	3.49	4.31	6.30

The system components used to develop the costs are listed in **Table 3**. Total capital and operating costs are summarized in **Table 4** as cost per tonne against distance.

Figures 1 and 2 show the cost BEPs for bauxite transportation by rail and by pipeline at capacities of 10 Mt/y (Figure 1) and 20 Mt/y (Figure 2) over rugged terrain in Cameroon, Guinea, Brazil, and Vietnam. In both cases, Vietnam is an outlier compared with the other countries, which are closely aligned. This is because the Vietnamese wage rates are lower than the others. Discounting Vietnam, it is seen that for both the 10 Mt/y and 20 Mt/y capacities, the BEPs are similar, ranging from 450 to 600 km and 450 to 650 km, respectively. This shows that the BEP is largely independent of transport capacity. It should be noted that the BEPs in the two figures pertain only to the case studies selected and will vary for other locations.

Figures 1 and 2 suggest that pipeline transport does not become economical until the transport distance reaches about 450 km. The capital cost of components is the determining factor. For rail, the greater the distance, the more rolling stock (to maintain unit-train cycle time and bauxite delivery rate), sleepers, and rail are needed. For pipeline, the greater the distance, the more pumps (to maintain bauxite delivery rate) and pipe are needed. Cost-wise, pipeline components are cheaper to buy, replace, and augment than are rail components.

It should be noted that where the BEP for rail/pipeline occurs, the unit-cost-versus-distance curves intersect at acute angles. This means that a small change in cost for either rail or pipeline results in a large shift in BEP. For example, if the pipeline cost varies by ±10% of the estimated cost, the BEP range changes as shown in **Table 5**. Thus, the BEP could range from 350 to 800 km, a significant departure from the base case range of 450 to 600 km.

Table 5. Sensitivity Range of Cost BEPs, 10 Mt/y System

BASE CASE	BASE CASE –10%	BASE CASE +10%
450–600 km	350–450 km	600–800 km

MBP BAUXITE SLURRY PIPELINE IN BRAZIL [1]

At the MBP facility in Brazil, bauxite is pumped through a 245 km pipeline across remote and rugged terrain to the Alunorte Refinery. This pipeline system became an economical transport mode because of factors favorable to a pipeline solution but not to a rail alternative, including

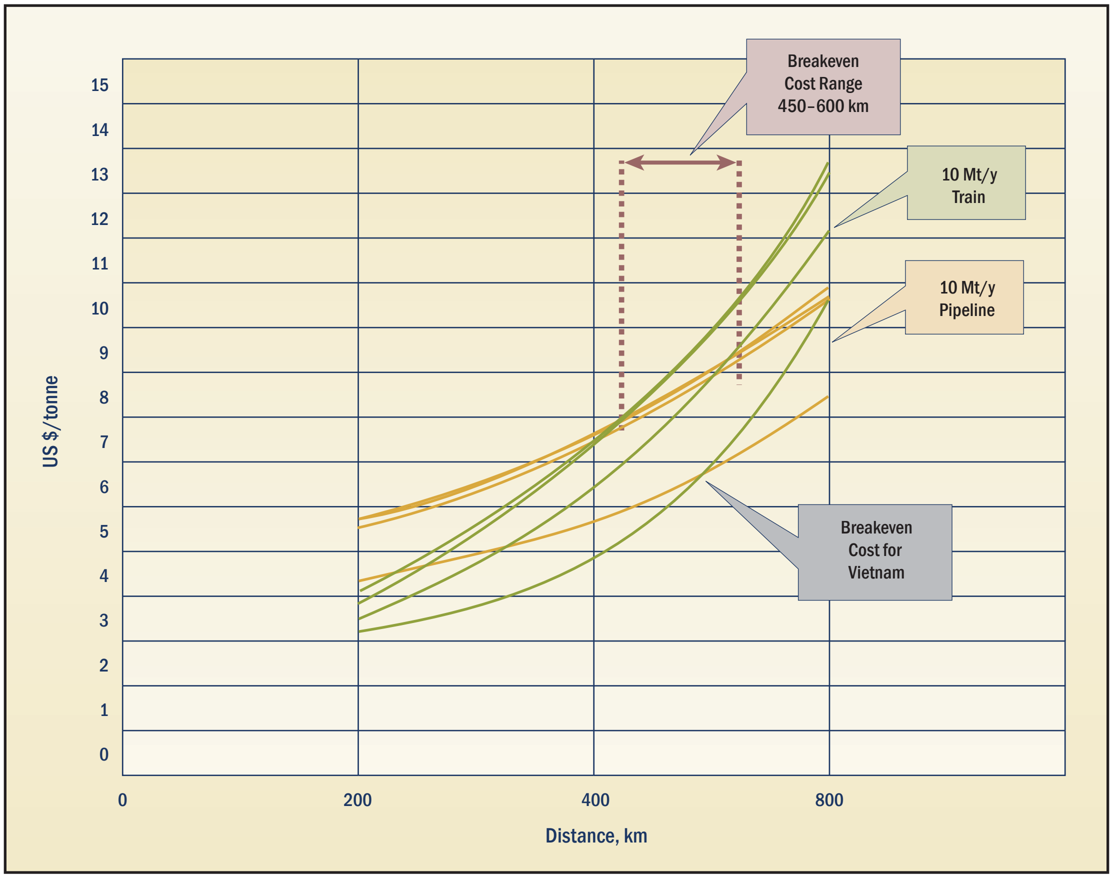

Figure 1. Bauxite Rail and Pipeline Cost Breakeven Points, 10 Mt/y System

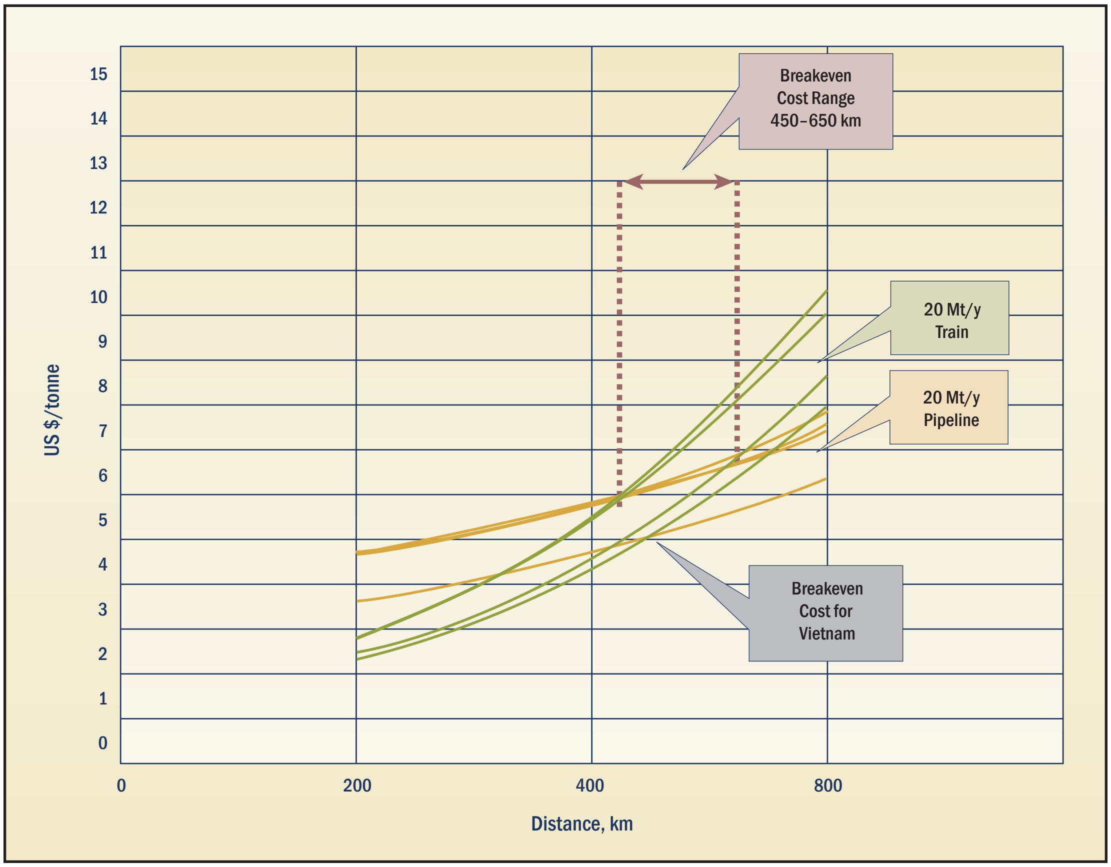

Figure 2. Bauxite Rail and Pipeline Cost Breakeven Points, 20 Mt/y System

location in a remote area; location in rugged terrain; use of an existing, cleared right-of-way; and the need for many stream crossings.

The MBP bauxite transportation system has the following slurry preparation, pipeline, and dewatering features.

The MBP pipeline has a leak detection system featuring five intermediate pressure-monitoring stations to indicate continuous pressure data to the pipeline operator.

Slurry Preparation Features

Slurry is prepared by crushing and grinding mined ore taken from stockpiles. Cyclones are used to adjust particle size. Tailings are separated and sent to a waste thickener. The prepared slurry at 50% solids is sent to agitated storage tanks next to the pipeline pump station. The pump station consists of six mainline crankshaft-driven piston diaphragm pumps connected in parallel. The pumps are Geho TZPM 2000 units from Weir Minerals Netherlands, each with a design capacity of 356 m^3/h and a maximum discharge pressure of 13.7 MPa.

Slurry Pipeline Features

The pipeline is designed for a future maximum annual production of 12.6 million tonnes of bauxite, but the initial capacity is only 4.5 million tonnes. The ultimate capacity will be reached after a few years, when the 610 mm (24 in.) diameter pipeline is fully used. Currently, the operation pumps slurry-water batches, a requirement to maintain slurry minimum design velocity. A second pump station will be needed to meet the additional pumping requirements for the future maximum production.

The pipeline has a leak detection system featuring five intermediate pressure-monitoring stations to indicate continuous pressure data to the pipeline operator. The pressure data is transmitted via a fiber-optic cable. The pipeline shares right-of-way with two existing kaolin slurry pipelines.

Slurry Dewatering Features

At the terminal station, agitator tanks receive the slurry to provide feed to the filter plant. The slurry is dewatered using hyperbaric pressure filters to produce a bauxite with about 12% moisture in the filter cake feed to the refinery.

SUMMARY OF PIPELINE TRANSPORT SYSTEM ATTRIBUTES

Table 6 summarizes the key advantages and disadvantages that need to be taken into account when considering a pipeline transport system.

Table 6. Advantages and Disadvantages of a Pipeline Transport System

ADVANTAGES	
Unobtrusive	Line buried, low visibility, low environmental impact, lower footprint
More Secure	Better protected, less likely to be vandalized
Safer	Local population better protected, no moving parts to clash with
Continuous Flow	No stop/start operation, less likely to experience product delay at refinery
Low Maintenance	None on pipeline, minor on pumps, high on filters
Flexible Alignment	Easily adjustable around villages or obstacles
Shorter Route	Fewer vertical and horizontal alignment constraints, resulting in more direct route
Easier Stream Crossings	Can pass buried under streams without bridging
Environmentally Friendly	Lower footprint, less clearing, does not isolate habitat, no noise/dust
DISADVANTAGES	
High Capital and Operating Costs	Slurry Preparation—high capital and operating costs from mine to pipeline for slurry preparation (crushing, grinding, water supply, etc.) Slurry Dewatering—high capital and operating costs for slurry receiving, dewatering filters and associated compressors, cake storage and re-slurrying, water disposal
Water Usage	Large water requirement for slurry transport (approximately 1 tonne of water per tonne of bauxite)
Rheology Change	Change in ore characteristics can change particle distribution, leading to possible increase in pumping head and increased filtering
Blockages	May be difficult to locate and remove
Dewatering Management	Expensive to return filter water to mine; disposal at refinery may require treatment before release; downstream issues, including environmental and community, may occur
Pipeline Life	Long-term pipeline performance, higher-than-expected internal corrosion and erosion

CONCLUSIONS

Long-distance transport of bauxite by pumping slurry through a pipeline is in its infancy, with only one operation at present, worldwide. This operation is at the MBP facility in Brazil, which has been pumping bauxite slurry 245 km across rugged terrain for only about 1 year. To date, there have been no reported problems.

Transporting bauxite slurry by pipeline may be the preferred solution over transporting dry bauxite by rail if a number of the favorable selection criteria listed in Table 6 are met. However, pipeline transport is likely to be used only in special cases, and selection must proceed with caution. There are a number of risks associated with pumping bauxite, as outlined in this paper. However, if the risks are addressed and properly managed, an economic advantage can be realized.

Compared with the long-distance rail transport of bauxite, slurry pumping becomes more economical over distances beyond 450 km for the cases presented in this paper. However, in contemplating the transportation of bauxite slurry by pumping it through a pipeline, it is essential to completely understand the properties and characteristics of the bauxite.

In the final analysis, each project is different and site dependent. Thus, even if the distance is long, the terrain is rugged, and the bauxite properties are known, much detailed analysis is still required before an informed decision can be made. ■

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BIOGRAPHY

Terry Cunningham is a senior civil engineer with 39 years of experience in planning, investigating, designing, and supervising the construction of a diverse range of large-scale infrastructure works, particularly in the mining and metals sector. He has spent the last 14 years with Bechtel and is currently based in Brisbane, Queensland, Australia, in the Alumina and Bauxite Centre of Excellence. His areas of expertise include earthworks, tailings disposal, water management, water resources, haul roads, dams, mine dewatering, drainage, flood mitigation, sewerage treatment, pumping systems, feasibility studies, and report writing.

Terry has worked throughout Australia and in Oman; Bahrain; Montreal, Quebec; Indonesia; and Papua New Guinea. Representative Bechtel assignments include serving as lead civil engineer on the Sohar aluminum smelter project in Oman, managing the design requirements for the complex licensing process required by the Queensland Government for the Pasminco Century zinc tailings dam, and designing and managing an important environmental cleanup project for the Comalco Bell Bay aluminum smelter in Tasmania. He presented a paper on this award-winning project to an international conference hosted by the Minerals Council of Australia at Newcastle near Sydney.

Before joining Bechtel, Terry worked for BHP Engineering on many coal infrastructure projects and on a major upgrade of the Brisbane-to-Cairns railway. The railway work involved replacing more than 300 old timber bridges (built in 1906) with large box culverts and bridges.

Terry qualified in Civil Engineering at Swinburne University of Technology, Melbourne, Australia. He is a member of the Institution of Engineers Australia and a registered professional engineer. Terry lectured part-time for 2 years at Royal Melbourne Institute of Technology.

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