REVIEW OF RECENT SLURRY PIPELINES AND THE ROLE OF PARTICLE SIZE IN DETERMINING THE DISTANCE BETWEEN PUMP STATIONS IN A LONG DISTANCE SLURRY PIPELINE

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ABSTRACT

The design of three Australasian slurry pipelines is reviewed. The 18 km New Zealand Steel iron sand pipeline (the world's first slurry pipeline to pump iron sand using positive displacement pumps), the 62 km OneSteel Whyalla magnetite pipeline (the first slurry pipeline to include a return water pipeline), and the 304 km Century zinc/lead concentrate pipeline (the longest single pump station slurry pipeline in the world and the first to involve batching of different concentrates).

The three pipelines cover the extremes of particle size suitable for long distance transport. The coarse particle NZ Steel pipeline requires 20 MPa pump pressure for 18 kms whereas the very fine particle Century pipeline only requires 18 MPa for 304 kms. The OneSteel pipeline transports a more typical size concentrate and requires 15 MPa for 62 kms. The role that particle size plays in the design of slurry pipelines is discussed and the likely pump station distances for future projects for various commodities indicated.

1. INTRODUCTION

Slurry Systems Engineering Pty Limited (SSE) personnel were involved in the design of many of the early slurry pipelines including the Savage River magnetite pipeline, the Black Mesa coal pipeline, the Gladstone limestone pipeline and the Irian Jaya, the Bougainville, and the Ok Tedi copper concentrate pipelines. However the current paper focuses on just three pipelines with SSE involvement, including the most recent pipeline in Australia, the OneSteel Whyalla magnetite pipeline commissioned in 2007.

SSE provided the definitive designs for the 18 km New Zealand Steel iron sand pipeline (2 x 10 MPa pump stations) and the 62 km OneSteel Whyalla magnetite pipeline (1 x 15 MPa pump station), and the basic hydraulic design for the 304 km Century zinc/lead concentrate pipeline (1 x 18 MPa pump station). The NZ Steel pipeline was the world's first slurry pipeline to pump iron sand using positive displacement pumps. The OneSteel pipeline is the first to include a return water pipeline. The Century pipeline is the longest single pump station slurry pipeline in the world and the first to involve batching of different concentrates (zinc and lead).

Each of these three pipelines traverses relatively flat terrain. With two pump stations, the NZ Steel pipeline effectively requires 20 MPa pressure for 18 kms whereas the Century pipeline only requires 18 MPa for 304 kms. The wide variation in pumping distances is due to the differences in particle size. The differing particle sizes required special considerations during design.

2. NEW ZEALAND STEEL IRON SAND PIPELINE

The World's first pipeline loading of bulk mineral commodities aboard a tanker offshore, without a deep water port was successfully completed on July 5, 1971, at Waipipi, New Zealand. The Waipipi shiploading system was based on single point oil tanker loading systems developed for the oil industry.

The success of the Waipipi system over a period of 12 years assisted in the development of a unique technical step in slurry technology resulting in NZ Steel's long distance ironsands pipeline from Taharoa to Woolf Fisher Steel Mill in South Auckland, a distance of 18 km. The NZ Steel pipeline designed by Slurry Systems was an extension of experience from both Savage River and Waipipi ironsands technologies.

2.1 Project Development

Ironsand concentrate has the following typical properties:

Specific Gravity	4.76
Narrow size distribution	(94% between 212 and 75 microns)
Mean Particle Size	120 micron
p_{80}	150 microns

Slurry Systems was convinced that positive displacement pumps and lined pipe were essential to satisfy the design requirements. Positive displacement pumps have three advantages over centrifugal pumps:

- High head capability, minimising the number of pump stations required.
- Pump discharge flow rate is independent of discharge head, ensuring that transport velocity is maintained independent of operating conditions.
- Pump efficiency is high, minimising installed and operating power.

A two pump station, 200 NPS system operating at 50% solids and a maximum pressure of 10,000 kPa was selected for design.

Lined pipe offers the potential to provide a pipeline capable of satisfying the design life without maintenance or replacement, allowing the pipeline to be buried as a conventional high pressure slurry pipeline. A polyurethane lined pipe offered the most economic solution. However, three unique technical issues required development testing prior to detailed engineering **–**

- Were PD pumps capable of reliably pumping high specific gravity coarse granular material without excessive maintenance or operator attention?
- Was polyurethane lined pipe capable of withstanding 25 years of operation at high and cyclic operating pressures?
- A welded pipeline joint, which required development for polyurethane lined pipes, was preferred.

2.2 Pump Testing

Tests were conducted by potential pump suppliers in Holland and Texas (USA) to determine whether PD pumps could pump coarse ironsand. The concerns were:

- Would the rapid settling ironsand (25mm/s mean settling velocity) create an operational or a wear problem when superimposed on the velocity cycle of a PD pump?
- Could a pump be restarted after shutdown with ironsand slurry at normal concentration?
- Would suction lines plug?
- Would standard slurry valves perform reliably at the service pressure?

A model of each proposed pump constructed with Perspex viewing covers was tested. Figure 2.1 shows the fluid end used in the diaphragm and the flushed plunger pump, and indicates the areas of concern through the stroke. Each test showed there was sufficient turbulence during the stroke to prevent deposition, although settlement was evident during the low velocity portions of the cycle.

Further tests showed there was no problem restarting a pump after shutdown with slurry at normal concentrations. The pump cylinder on the suction stroke progressively fluidised the settled ironsand, while ironsand in the cylinder on the discharge stroke was displaced sufficiently for the stroke, without evidence of jamming. The diaphragm pump was assisted by the flexibility of the diaphragm, while the flushwater used in the plunger pump partially fluidised the settled solids ahead of the plunger.

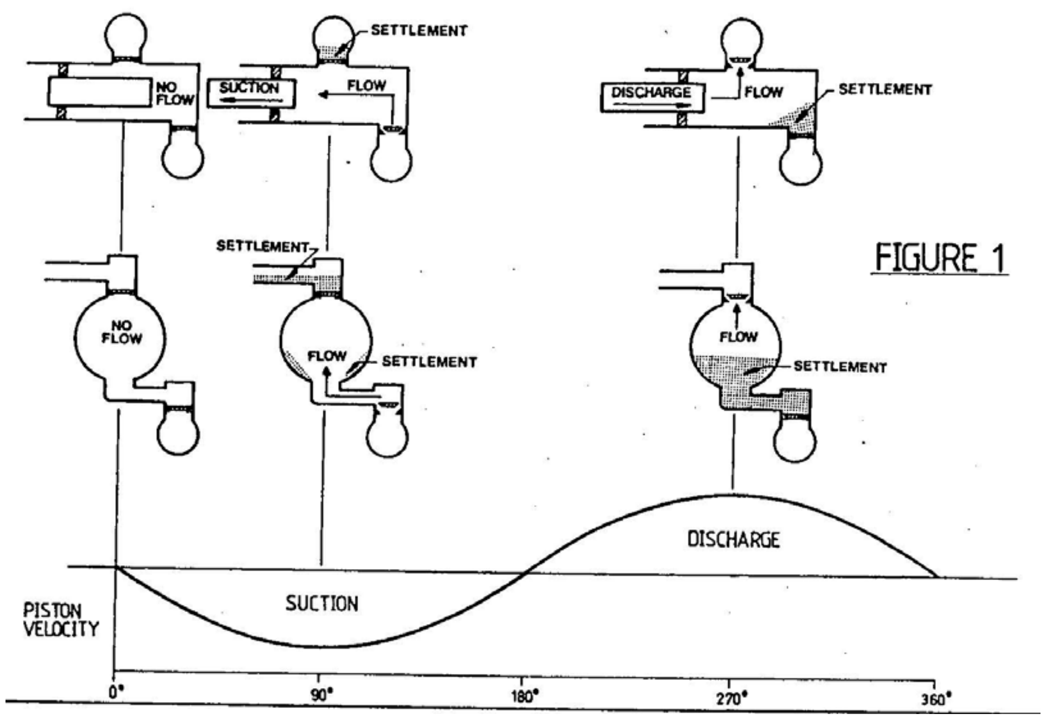


Figure 2.1 Areas of Concern with PD Pump Operation

2.3 Polyurethane Lined Pipe

The pipe problem was more difficult. Although polyurethane lining has been used in slurry pipelines since the 1970's, there was little published history, and certainly no history of service in long term high pressure ironsand pipelines. The designers were aware of negative opinions in some mining operations which were traced to costly failures resulting from poor application, rather than polyurethane failure in service.

Data obtained from rubber lined pipe in similar ironsand service for 9 years showed only minor wear. This experience, correlated with the limited information available for polyurethane pipe linings in the UK, USA and Australia, provided confidence in polyurethane lining.

2.4 Pipe Jointing

There was a strong preference for a welded pipeline over a mechanically jointed (flange or high pressure victaulic) jointed line because of the potential for failure in any of the 1,500 joints required. World experience with high pressure polyurethane lined pipe was, at that time, limited, and welded jointing was not practical because of damage to the lining.

M^c^Connell Dowell and Slurry Systems developed a coupling which allows welded pipe joints rated to ANSI Class 600 (Figure 2.2). Extensive testing was performed in New Zealand and the USA to prove the design could be welded without damage to the polyurethane, and without disbondment in a production welding environment, using stovepipe welding techniques. Continuous cooling is required from the time the root weld is completed until the final weld pass is completed to maintain the temperature at the polyurethane/steel bondline below 100 deg C (the temperature limit for disbondment). The weld quality was assured by radiographic examination and the bond quality by a continuous temperature record made at two points on each weld.

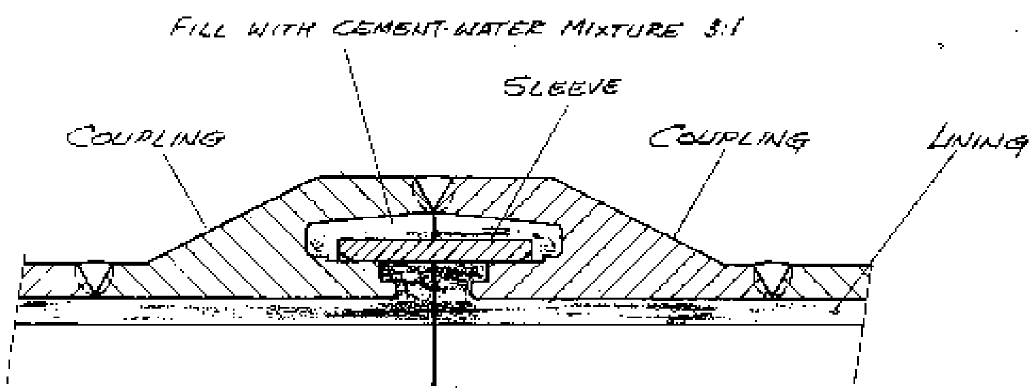


Figure 2.2 Typical Special Welded Coupling

2.5 Pipeline Hydraulics

The particle size analysis and specific gravity of the ironsand dictate a high energy heterogenous slurry pipeline. Care was required to select an operating velocity sufficiently above the deposit velocity to provide safe operation with minimum hold-up, while not penalising the operating cost.

The projected operating hydraulic gradient was calculated from the known solids properties. Full advantage was taken of the smooth finish provided by centrifugally cast polyurethane line pipe in determining the design hydraulic gradient. The final design is summarised in Table 2.1.

Table 2.1
Pipeline System Design

Minimum Operating Velocity Design Operating Velocity	3.6 m/s 3.9 m/s
Concentration	48.5 wt % solids (dry basis)
Pipeline Inside Diameter Pipeline Length Section 1 Pipeline Length Section 2	187.4 mm 9,200 m 8,800 m
Maximum Operating Pressure	ANSI Class 600

The NZ Steel pipeline system incorporates two pump stations, each with a discharge pressure of 9.9 MPa. In 1990, the NZ pipeline system was recognised as a world's first with a unique contribution (one of only seventy awards) to the engineering history in New Zealand.

3. ONESTEEL WHYALLA MAGNETITE PIPELINE

3.1 General Description, Whyalla Pipeline

The Whyalla pipeline transports magnetite concentrate 62km from the Iron Duke mine to Whyalla. A parallel water pipeline returns water from the dewatered slurry plus additional water back to the mine. Both pipelines are fully welded, unlined steel pipelines buried in a common trench. The slurry pipeline uses a single pump station with two Geho triplex piston diaphragm pumps, one duty and one standby, each driven by a 1050 kW variable speed motor and maximum discharge pressure is 15.3 MPa. The slurry pump station is located adjacent to the concentrator at the minesite. The magnetite slurry is received from the thickener into two 10 m diameter x 10 m high agitated slurry storage tanks at the pump station. Each agitator is driven by a 45 kW motor. Two variable speed centrifugal charge pumps, one duty and one standby, receive slurry from the agitated storage tanks and deliver the slurry at a controlled pressure to the mainline piston diaphragm pumps. The return water pipeline uses a single pump station utilising two stage Sulzer centrifugal water pumps. SSE performed detailed design of the pipelines and provided assistance during commissioning. The pipelines were commissioned in August

2007. Both pump stations include lime and chemical injection facilities to control internal corrosion of the unlined pipelines. The pipeline operating procedures include regular monitoring for internal corrosion.

3.2 Whyalla Slurry Properties

Table 3.1 summarises the typical slurry properties.

Table 3.1 Whyall pipeline - typical slurry properties	
Concentration (wt%)	62.5
Solids SG	5
Particle Size (Microns) p_{95} p_{80}	70 42
Bingham Yield Stress (Pa) Plastic Viscosity (mPas)	3.5 6.35

Slurry batch properties are measured prior to committing them to the pipeline. Sampling points are installed on the side of the bottom of each tank. Samples are collected and rheology measured in the laboratory. The pump station does not have a test loop.

3.3 Whyalla Slurry Pipeline Hydraulics

From 2005 onwards SSE conducted laboratory tests on various samples. The Whyalla pipeline design was based solely on laboratory tests on 20 litre slurry samples in SSE's laboratory, with no loop tests conducted and no test loop is installed. The Whyalla design was based on the use of OneSteel manufactured steel pipe.

The design hydraulic gradient is shown in Figure 3.1. The pipeline wall thickness is telescoped in order to reduce pipe steel requirements from 8.2mm to 4.8mm generally reducing towards the low pressure end.

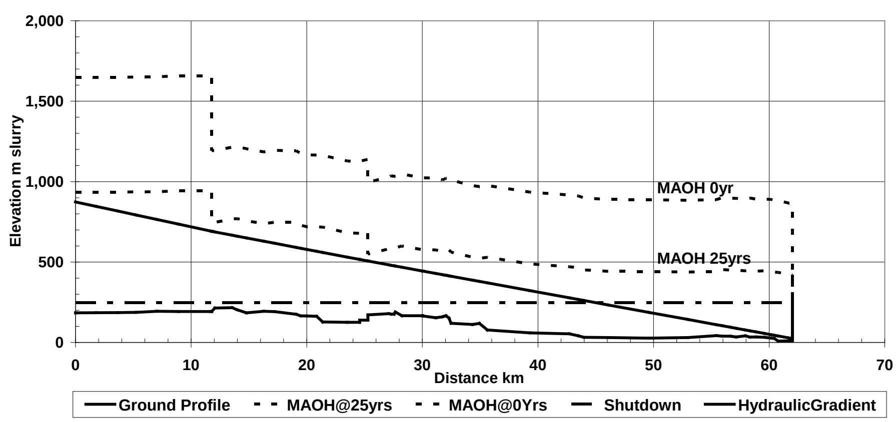


Figure 3.1 DN200 Slurry Pipeline Hydraulic Gradient

No air release valves are installed on either the slurry or return water pipelines and the pipelines follow the ground undulations with no special grading of the pipelines. No mainline isolation valves are installed along the length of the pipeline. For the initial year of operation only a single mainline piston diaphragm pump was installed in the pump station. Consideration was given to the possibility of a long term failure of the single mainline pump with a line full of slurry and the potential methods available to flush the slurry from the pipeline. Analysis by SSE indicated that it would be possible to flush the slurry pipeline in sections using pressurised water from the parallel return water pipeline. The crossover connections between the slurry pipeline and the return water pipeline are installed at high points at km 13.8 and km 28.3. A standby mainline slurry pump has recently been installed.

Commissioning tests included shutdown and restart of the pipeline full of slurry after a period of 24 hours.

4. CENTURY ZINC/LEAD CONCENTRATE PIPELINE

4.1 General Description, Century Pipeline

The Century pipeline transports zinc and lead concentrates 304 km from the Century mine in NW Queensland to Karumba on the Gulf of Carpentaria. Slurry Systems was involved in the Century pipeline project from the earliest investigations in 1992, through to commissioning in 1999, and in a number of operational reviews since then. The Century pipeline has a single pump station with three Wirth TPM 83/4 x 14 piston diaphragm type pumps operating in parallel, each driven by a 1130 kW motor. There are pressure monitoring stations along the pipeline to provide pressure information and leak detection monitoring. Leak detection is also monitored by comparing magnetic flow meter readings at the pump station and at the terminal. The DN300 pipeline is 323.9 mm OD with steel wall thickness varying from 8.4 mm to 4.8 mm, with an inserted 7.5 mm HDPE liner. The Century pipeline has perhaps the flattest profile of any slurry pipeline, commencing at an elevation of 155 m and ending at an elevation of 15 m.

There are four 12.5 m high x 12 m diameter agitated tanks at the pump station, three for zinc concentrate and one for lead concentrate. Each tank has a live capacity of approximately 1150 m^3 representing about 4 hours pumping capacity. The zinc tanks are fitted with Lightnin agitators powered by 55 kW motors. The lead concentrate tank has a 75 kW agitator. There are three 13 m high x 12 m diameter tanks at the Karumba terminal, two zinc concentrate and one lead concentrate, fitted with similar 55 kW and 75 kW agitators respectively.

4.2 Century Slurry Properties

Table 4.1 summarises the typical slurry properties.

Table 4.1 Century pipeline - typical slurry properties		
	Zinc Conc.	Lead Conc.
Concentration (wt%)	35	37
Solids SG	4.1	4.8
Particle Size (Microns)	15	37
p_{95}	7.5	18
p_{80}	3	6
p_{50}		
Bingham Yield Stress (Pa)	1.0	0.5
Plastic Viscosity (mPas)	4.0	3.5

Slurry batch properties are measured prior to committing them to the pipeline. Sampling points are installed approximately 2 m from the bottom of each tank. Samples are collected and particle size, solids concentration and rheology measured in the laboratory.

An additional control measure is provided by an SSE On-Line Viscometer which continuously measures the slurry entering the suction of the mainline pumps and controls the Yield Stress by automatic dilution as required. A test loop is installed at the pump station and was used during commissioning to assess slurry pumping suitability and confirm predictions. The test loop is not generally used in day to day operations unless a particularly unusual slurry is encountered. The Century test loop consists of two 100 m long straight legs with a 5D radius bend at the end. The test loop is fitted with a magnetic flow meter, a nuclear density gauge mounted at 45^0 across the horizontal pipe and a differential pressure transmitter. Sampling tubes are mounted at top, middle and bottom of the pipe.

4.3 Century Pipeline Hydraulics

A major driving force in the Century design was to try and achieve only a single pump station. Based on typical slurry pipeline experience at that time, two pump stations would have been automatically selected for the 304 km distance. However a remote booster station would have presented difficulties during the wet season when much of the route is flooded. In fact the annual flooding of the route was why a slurry pipeline was the only feasible transport option.

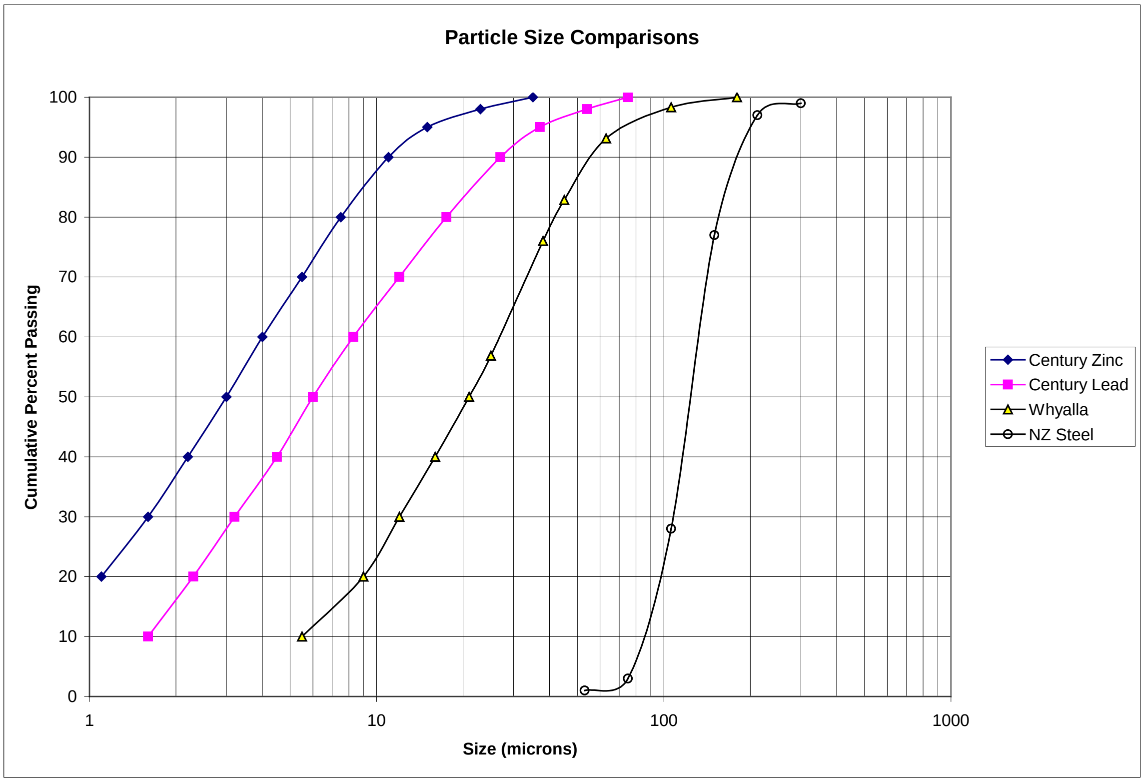
From 1992 onwards SSE conducted laboratory tests on various samples. After numerous pipeline option studies it was eventually decided that, because of the very fine particle size, the design velocity could be reduced to as low as 1.2 m/s, much lower than the 1.6 m/s to 1.8 m/s of typical concentrate pipelines. This reduced velocity meant the head loss gradient is about 4 metres of slurry/km, half that of other concentrate pipelines, allowing a single pump station. The Century pipeline design was based solely on laboratory tests on 20 litre slurry samples performed in SSE’s laboratory, with no loop tests conducted other than on-site confirmatory testing during commissioning.

Typical operation involves four to six hour batches of zinc concentrate with a one hour water batch in front and a two hour water batch behind each lead concentrate batch. Water batches of varying length are also sometimes inserted between zinc concentrate batches primarily to match pipeline capacity with production with the aim of keeping the pipeline operating continuously.

5. THE ROLE OF PARTICLE SIZE

Figure 5.1 compares the particle size distributions for Century zinc and lead concentrates, Whyalla magnetite, and NZ Steel iron sand. p_{80} particle sizes are respectively 7.5, 17.5, 42, and 150 microns. Note the NZ Steel iron sand has a much narrower distribution than the other three concentrates.

Figure 5.1

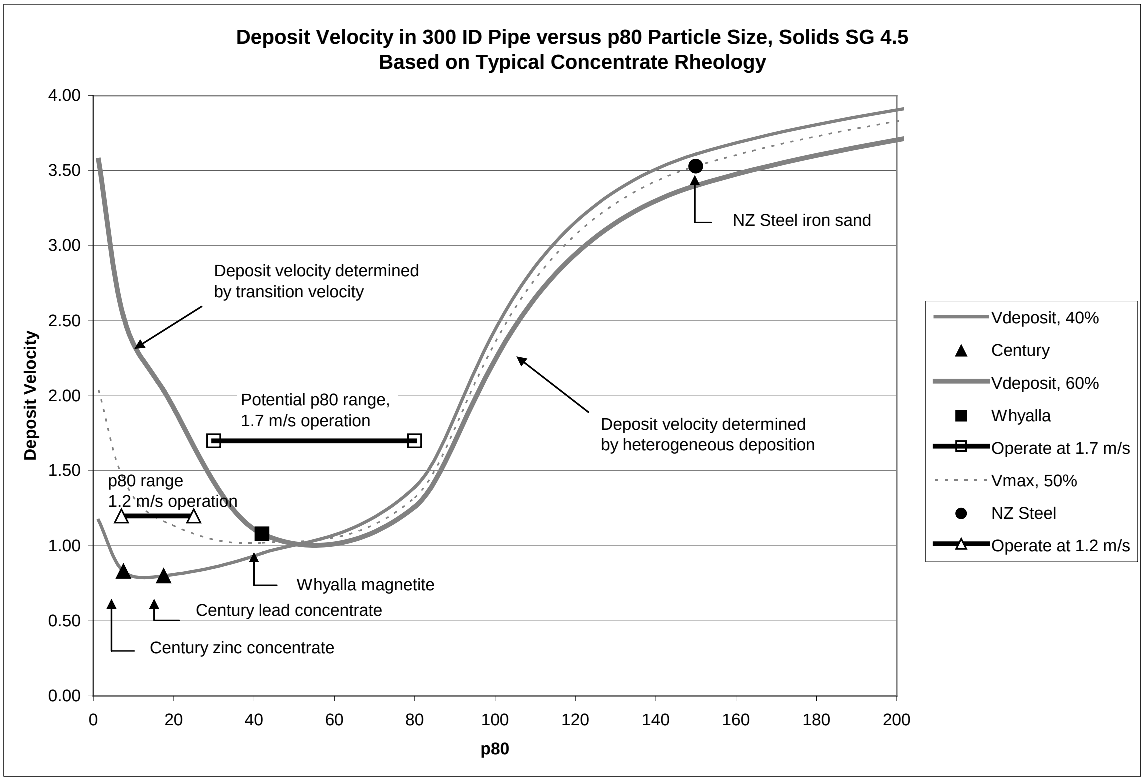


Long distance slurry pipelines must operate in the turbulent regime and at a velocity 0.2 to 0.3 m/s above the deposit velocity to maintain particles in suspension. Deposition is determined either by heterogeneous effects or by transition to laminar flow.

The very fine particle size of the Century zinc and lead concentrates (p_{80} 7.5 and 18 microns respectively), and the resulting low deposition velocity, is the reason why the operating velocity was able to be reduced to the range 1.1 to 1.2 m/s with the result that only one pump station is required to pump 304 kms.

Figure 5.2 shows the predicted deposit velocity (due either to heterogeneous deposition or laminar-turbulent transition) versus p_{80} particle size for concentrates of solid SG 4.5 in a 300 mm ID pipe based on assumed typical concentrate rheology. SG 4.5 is close to the SG 4.67 of NZ Steel iron sands and is approximately midway been Century zinc concentration SG 4.1 and Whyalla magnetite SG 5.0. The predicted deposit velocity is shown for 40% and 60% concentration with the intermediate 50% concentration shown dashed.

Figure 5.2



In Figure 5.2, the U shaped 60% concentration curve has a minimum around p_{80} = 55 microns. As the p_{80} size reduces below 55 microns, the rheology increases, raising the transition velocity, which then determines the deposit velocity. For p_{80} sizes above 55 microns the rheology decreases, the transition velocity becomes irrelevant and the deposit velocity is determined by heterogeneous deposition.

Considering the p_{80} sizes (7.5 and 18 micron) pumped in the Century pipeline, Figure 5.2 shows how it is necessary to reduce the concentration to below 40% to allow operation at 1.2 m/s while still providing 0.2 m/s to 0.3 m/s margin above the deposit velocity. If the concentration was 60% the operating velocity would need to be increased to around 3 m/s to get above the deposit velocity, requiring a pump station every 10 or 15 kms similar to the NZ Steel pipeline, and making the Century pipeline totally uneconomic. Note that the p_{80} range for 1.2 m/s operation at 40% concentration extends to around 25 microns. This is in agreement with experience at Century where coarser lead concentrate with p_{80} around this size has been pumped successfully.

The 40% maximum concentration applying to the Century pipeline is a special case because of the extremely fine particle size. For more typical concentrates such as the Whyalla magnetite, increasing the concentration to 60% to 70% proves most economic.
As the particle size coarsens, the deposit velocity increases and the operating velocity must be increased. Thus for OneSteel Whyalla magnetite with p_{80} 42 microns, the operating velocity was increased to around 1.7 m/s.

Figure 5.2 indicates that, based on the assumed rheology, p_{80} sizes up to 80 microns can be pumped at an operating velocity of 1.7 m/s. As the p_{80} size increases above 80 microns the deposit velocity increases rapidly reaching a predicted 3.53 m/s in the 300 ID pipe for the p_{80} 150 microns NZ Steel iron sand at 50% concentration, indicating an operating velocity around 4 m/s. (The NZ Steel pipeline operates at 3.6 m/s because the deposit velocity is less in the smaller 187 mm ID pipe).

To summarise, the Century pipeline can operate at 1.2 m/s because of the very fine particle size and the reduced concentration. The Whyalla pipeline operates at 1.7 m/s because of the coarser particle size and the increase in concentration to above 60%. The NZ Steel pipeline operates at 3.6 m/s due to the much coarser particle size and lack of viscous support because of the low fines content.

For these “long distance” type slurries the head loss gradient is roughly proportional to velocity squared. Hence the head loss gradient for Whyalla magnetite will be $(1.7/1.2)^2$ or approximately two times the head loss gradient of Century concentrate, requiring twice as many pump stations. The head loss gradient for NZ Steel iron sand will be $(4/1.2)^2$ or approximately eleven times the head loss gradient of Century concentrate, requiring eleven times the number of pump stations. Head loss gradient also varies roughly inversely with pipe diameter and this needs to be taken into account when comparing the number of pump stations in the 200 mm Whyalla and NZ Steel pipelines with the 300 mm Century pipeline.

Figure 5.2 applies to 300 mm ID pipe. However the curves will be very similar for larger pipe sizes. The rising curves on the left hand side of Figure 5.2 will not change with pipe size because the transition velocity of a Bingham plastic is independent of pipe diameter. In the heterogeneous deposition controlled portion of the curves to the right of the minimum, the deposit velocity does increase with pipe diameter but only slightly for moderate size particles. For example, based on the assumed typical rheology, the deposit velocity at 60% concentration for p_{80} = 80 microns is only predicted to increase from 1.26 m/s in the 300 ID pipe to 1.41 m/s in a 900 ID pipe. There is a greater increase in deposit velocity for coarser particles. For example the deposit velocity at 60% concentration for p_{80} = 150 microns is predicted to increase from 3.40 m/s in the 300 ID pipe to 4.63 m/s in a 900 ID pipe.

6. HEAVY MINERAL SANDS – POTENTIAL FOR REDUCING THE HEAD LOSS GRADIENT

Figure 5.2 illustrated how, based on assumed typical concentrate rheology, once the p_{80} size increases above about 80 microns, the deposit velocity increases rapidly, dictating higher operating velocities and resulting in a steep increase in head loss gradient. A potential means of reducing the head loss gradient for narrow size distribution heavy mineral sands similar to the NZ iron sand, involves pumping the sand in slimes. The slimes effectively reduce the average particle size of the slurry. Also the higher viscosity of the slimes compared with water reduces the heterogeneous dependant deposit velocity. Heavy mineral sands are often present with slimes which are normally separated at the mine site. If, for environmental reasons, a slurry pipeline is required to include a return water pipeline, the option exists of pumping some, or all of the slimes with the sand, separating the sand from the slimes at the pipeline terminal and returning the slimes in a return pipeline. i.e. the slimes plus water are recycled rather than just water.

As an indication of the potential benefits, preliminary predictions using a particular slimes at 17% concentration as the carrier fluid in the 300 ID pipe, suggests the deposit velocity for the NZ iron sands could be reduced from 3.53 m/s in water to around 2.4 m/s in the slimes. In a 900 ID pipe the predicted deposit velocity reduces from 4.86 m/s in water to around 2.8 m/s in the slimes, with the result that only about one third the number of pump stations are required.

7. CONCLUSIONS

Three slurry pipeline projects have been described: the New Zealand Steel iron sand pipeline; the OneSteel Whyalla magnetite pipeline; and the Century zinc and lead concentrate pipeline. SSE had a major involvement in each of these pipelines. The three pipelines cover the full range of particle sizes suitable for long distance pipeline transport.

The deposit velocity determines the transport velocity and hence the head loss gradient. The dependence of deposit velocity on particle size and concentration has been illustrated and discussed for concentrates of solids SG 4.5 and assumed typical rheologies. If the p_{80} size is less than about 25 microns and the concentration is kept below about 40%, it is possible to pump extremely long distances with one pump station such as the 304 kms at Century. For more typical concentrations around 60% and p_{80} sizes up to about 80 microns, the spacing between pump stations decreases to about half that at Century. Once the p_{80} particle size increases above about 80 microns the deposit velocity increases rapidly and pumping distances decrease markedly. For all slurries the number of pump stations required decreases roughly in proportion to the pipe diameter.

For most economic slurry transport the p_{80} size needs to be less than about 80 microns (for solids SG 4.5). The p_{80} limits shown in Figure 5.2 are based on the assumed typical concentrate rheologies and the limits could vary moderately either way depending on the actual rheologies.

For narrow size distribution heavy mineral sands, potential savings exist by transporting the sands in the naturally occurring slimes and recycling the slimes in a separate return pipeline.

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