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COMPARING PREDICTED DEPOSIT VELOCITIES WITH OPERATING VELOCITIES IN FOUR LONG DISTANCE CONCENTRATE PIPELINES

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ABSTRACT: Predicted deposit velocities have been compared with operating velocities in four concentrate pipelines: The 155 km Ok Tedi copper concentrate pipeline in PNG, the 304 km Century zinc/lead concentrate pipeline in Australia, the 301 km Antamina copper/zinc concentrate pipeline in Peru and the 62 km Whyalla iron concentrate (magnetite) pipeline in Australia. Concentrate slurry properties are listed and methods used to predict the deposit velocity noted and referenced. Comparing predicted deposit velocities with operating velocities allows the velocity margin for each pipeline to be compared. Velocity margins range from 0.25 m/s to 0.86 m/s and reasons for the differences are discussed. It is concluded that, in the four operating pipelines, the deposit velocity is generally determined by viscous sub-layer deposition rather than laminar transition deposition.

KEY WORDS: deposit velocity, long-distance concentrate slurry pipelines,

NOTATION

Cv	Concentration of solids by volume
Cw	Concentration of solids by weight
d80	Particle size, 80% passing
SG	Specific gravity solids (density) (t/m^3)
Vd	Deposit velocity (m/s)
Vdhet	Heterogeneous deposit velocity (m/s)
Vdt	Transition deposit velocity (m/s)
Vdvsl	Viscous sub-layer deposit velocity (m/s)
Vr	Volume ratio solids

1. INTRODUCTION

The operating velocity of a long-distance slurry pipeline is selected to be a safe margin above the deposit velocity (Vd). This paper investigates four operating long-distance concentrate pipelines. Information on the concentrates such as solids SG, particle size, and rheology, is provided and methods for predicting the deposit velocities are discussed. The predicted deposit velocities are compared with the operating velocities. The four pipelines are:

- Ok Tedi copper concentrate pipeline, Papua New Guinea, commissioned in 1987
- Century zinc and lead concentrate pipeline, Australia, commissioned in 1999
- Antamina copper and zinc concentrate pipeline, Peru, commissioned in 2001
- Whyalla magnetite pipeline, Australia, commissioned in 2007.

The author was involved in the commissioning of each of these four pipelines.

Ok Tedi

The Ok Tedi pipeline transports copper concentrate from the Ok Tedi mine, at an elevation of 1540 m in the mountains of Papua New Guinea, 155 km to Kiunga, a port on the Fly River, from where it is filtered and dried then barged down the river, 740 river kilometres to the Gulf of Papua. The pipeline is unlined. Figure 1, taken from Venton and Boss (1996), shows the route profile, the Maximum Allowable Operating Head (MAOH), and the Hydraulic Gradient Line (HGL). Flow is by gravity for the first 97 kms and then pumped from Km 59. Note: Kilometres shown are measured from the terminal.

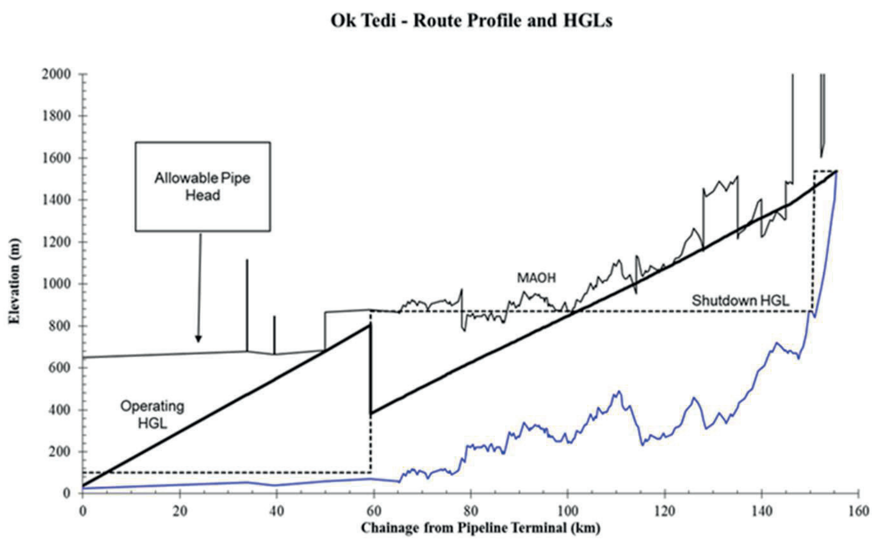

Figure 1

Century

The Century pipeline batches zinc and lead concentrates from the Century mine in NW Queensland, Australia, 304 km to Karumba at the mouth of the Norman River on the Gulf of Carpentaria, where it is filtered and dried then transported by barge and loaded on to ships moored in the Gulf. The hydraulic design of the pipeline was by Slurry Systems with detailed design by a Joint Venture between Pasminco, Minenco and Bechtel, with construction by Bechtel. The Century pipeline is the longest single pump station slurry pipeline in the world and the first to batch different concentrates in separate batches. There is only 150 m difference in elevation from the mine to the terminal. The Century pipeline is HDPE lined.

Antamina

The Antamina pipeline batches copper and zinc concentrate in Peru. The pipeline was designed by Pipeline Systems Incorporated (PSI) and constructed by Bechtel. It starts high in the Andes mountains at 4,200 m and descends to sea level. Over the initial 125 km there is little gravity assistance and pumping is required in the DN250 pipe. Thereafter the flow is basically by gravity, with smaller DN200 pipe used between Km 125 and Km 180 together with three choke stations to dissipate excess head. The Antamina pipeline is HDPE lined. Figure 2, from Thomas et al (2002), compares the Century and Antamina Route Profiles and HGLs. Note: In Figure 2 the Antamina HGL shown is for water from Km 100 onwards.

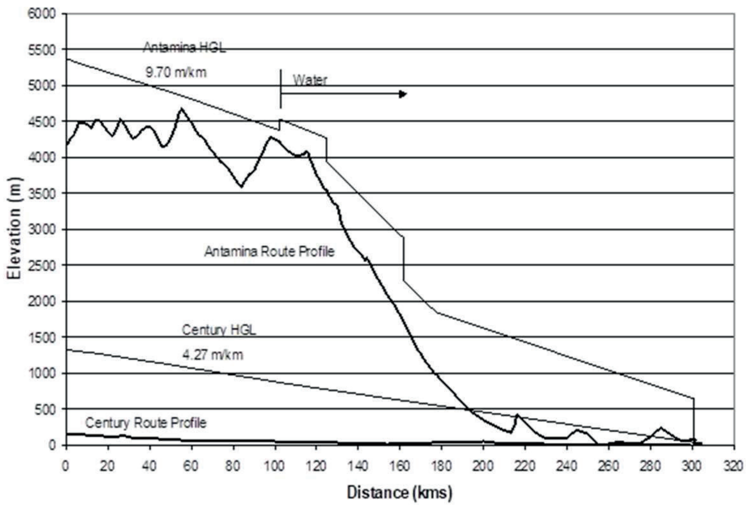

Figure 2

Whyalla

The 62 km Whyalla pipeline in South Australia transports iron concentrate (magnetite) from the mine to the Whyalla Port. Pipeline hydraulic design was by Slurry Systems Engineering Pty Limited. The pipeline is unlined and was the first concentrate pipeline project to include a return water pipeline.

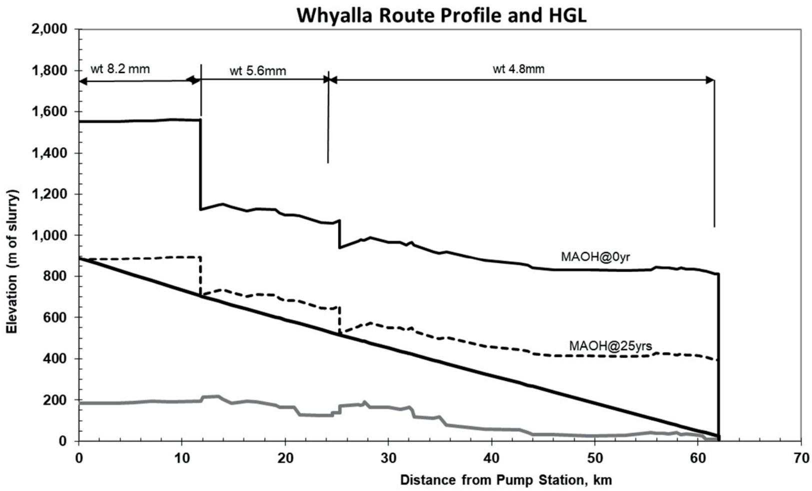

Figure 3

Tables 1 and 2 compare some relevant statistics of the four pipelines.

Table 1

Pipeline	Concentrate	Length (kms)	DN (mm) HDPE lined?	GravityHead (m/km)
Ok Tedi	Copper	155	150, No	10
Century	Zinc/Lead	304	300, Yes	0.5
Antamina	Copper/Zinc	301	250-200, Yes	14
Whyalla	Magnetite	62	200, No	3.2

Table 2

Pipeline	Flow Rate (m^3/h)	Largest/smallest ID (mm)	Operating Velocity (m/s)
Ok Tedi	85/88	157.1	1.22 / 1.26
Century	290 typical	299.3	1.14
Antamina	285 typical	246.1 / 179.6	1.66 / 3.13
Whyalla	169/205 *	209.5	1.36 / 1.65

* Note: During commissioning of the Whyalla pipeline a flow rate as low as 169 m^3/h was pumped. Typical operating flow rate is 205 m^3/h.

2. DEPOSITION IN SLURRY PIPELINES

2.1 THREE TYPES OF DEPOSITION

A recent paper by the author (Thomas, 2019), illustrated how deposition of a slurry in a particular pipe size, can be due to three causes. At low concentrations, heterogeneous deposition occurs. As the concentration increases, deposition occurs due to viscous sub-layer effects. With further increase in concentration, turbulent flow may be replaced with laminar flow. Once this occurs, deposition coincides with the laminar-turbulent transition velocity.

Figure 4, adapted from Thomas (2019), shows predicted deposit velocity (Vd) versus the observed Vd of Goosen and Paterson (2014), for gold tailings (solids SG 2.78) in a 100 mm ID test loop. Prediction methods used are referenced in the current paper. For more details of prediction methods refer to Thomas (2019).

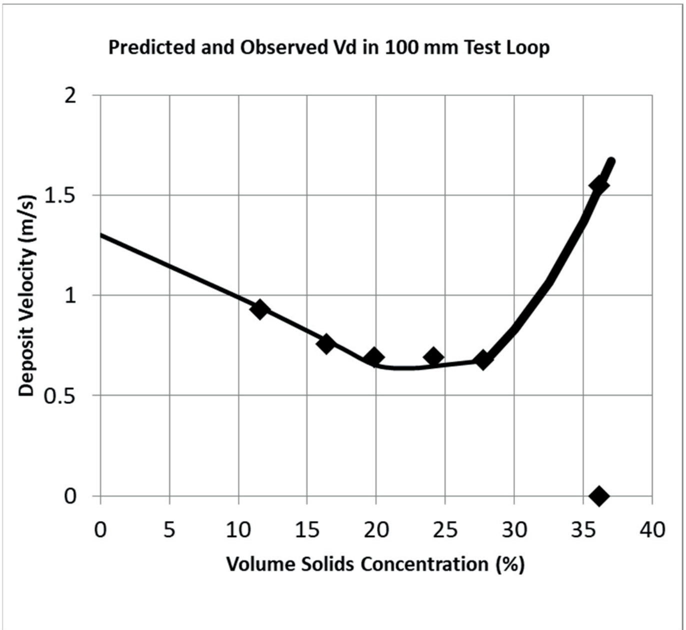

Figure 4

<u>Heterogeneous deposition</u>

The downwards sloping curve on the left side of Figure 4 is the <u>heterogeneous</u> deposition velocity prediction (Vdhet), occurring between Volume Concentration Cv=0% and about Cv=20%. As the concentration increases within this range, the increase in slurry density and viscosity, decreases the settling tendency of the coarser particles and so Vd decreases. The heterogeneous Vd is predicted using the Modified Wilson and Judge (MW&J) method of Thomas (2015).

Viscous sub-layer deposition

Between 20% and 28% concentration, viscous sub-layer deposition (Vdvsl) becomes predominant. Viscous sub-layer deposition applies in situations where, although all particles are fine enough to be supported by turbulence, deposition still occurs if particles are smaller than the viscous sub-layer. Such particles within the viscous sub-layer are not subject to turbulence and another deposition criteria applies.

Thomas (1979b) developed a deposit velocity prediction method for particles smaller than the viscous sub-layer, based on the Wilson sliding bed theory. Sanders et al (2004) modified Thomas' (1979b) viscous sub-layer theory to include the effect of particle size and concentration.

Laminar-Turbulent transition deposition

The laminar-turbulent transition velocity (Vt) is predicted using the equation of Wilson and Thomas (1985). The transition velocity depends on the yield stress and slurry density whereas heterogeneous and viscous sub-layer deposition depend on plastic viscosity and slurry density. Once the velocity falls below Vt, the flow becomes laminar and so deposition occurs due to transition. Hence, in this case, Vd= Vdt.

Above Cv=28% Vdt increases rapidly as it coincides with Vt, the laminar-turbulent transition velocity, Vt. However, the observed test loop deposition velocity at Cv=36.1% is shown as 0 m/s, rather than on the Vt curve. This is explained by, in the words of Goosen and Paterson (2014): *"these (high concentration) data indicate that for these tests, no stationary deposit was observed (even at velocities as low as 0.1 m/s) until the flow in the test loop was stopped entirely."* Hence Vt at Cv=36.1% was recorded as 0 m/s. The reason no stationary deposit was observed in laminar flow and Vd did not coincide with Vt, is because the test loop was not long enough for laminar settling to develop. It has long been known that some settling of coarser particles occurs as laminar flow proceeds along a pipeline, e.g. Thomas (1979a). It is now understood (e.g. Cooke, 2002) that if a pipeline is long enough, all non-colloidal particles will eventually settle in laminar flow. For such slurries in a long pipeline, turbulent flow is required for stable operation, and so Vd will equal Vt. Therefore, if the test loop had been long enough, the observed Vd data point at Cv=36.1% would equal 1.53 m/s on the Vt curve as shown by the additional data point in Figure 4.

2.2 RELEVANCE OF FIGURE 4 TO LONG DISTANCE CONCENTRATE PIPELINES

Suppose Figure 4 applied to a concentrate slurry in a long-distance pipeline. Such pipelines generally operate at a near constant concentration.

If the slurry is pumped at Cv=15%, flow is heterogeneous and Vd=0.8 m/s. However heterogeneous flow is not normally considered for long distance pipelines because of the likelihood of coarse particles dragging along the bottom of the pipe, resulting in bottom pipe wear. (Bottom wear, due to heterogeneous flow during trail-out, is discussed later in Section 5.3).

If the slurry is pumped at Cv=25%, the predicted Vd is 0.65 m/s, as per viscous sub-layer deposition. If the slurry is pumped at Cv=30%, the predicted Vd is 0.8 m/s, coinciding with the laminar transition velocity, Vt. Thus, deposition in long distance concentrate pipelines can be due to either viscous sub-layer deposition or laminar-turbulent transition.

3. CONCENTRATE PROPERTIES COMPARISON

Figure 5 compares particle sizings of the six concentrates on Rosin-Rammler (1933) coordinates. The Century zinc and lead sizings were obtained by a laser instrument. All other sizings are the result of screening down to 45µm or 32µm. Particle size distributions of material which has been subjected to a grinding process, generally plot as a straight line on Rosin-Rammler coordinates. The coarsest concentrate is Antamina zinc with 99% passing 0.175 mm (175µm). The finest concentrate is Century zinc with 99% passing 0.021 mm (21µm). Table 3 compares concentrate solids SG and pertinent particle size information.

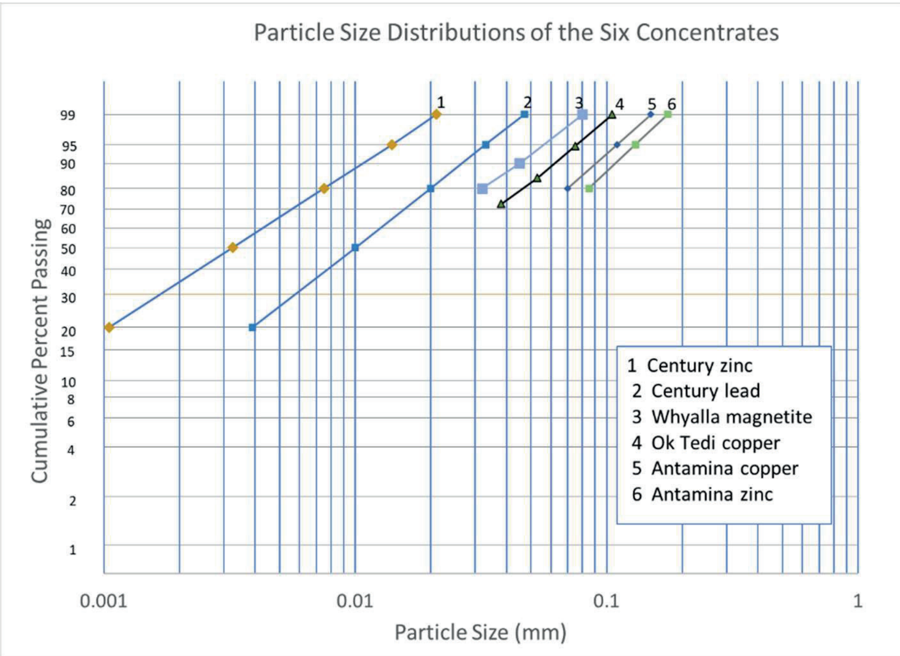

Figure 5

Table 3

	Solids SG	d50 µm	d80 µm	d95 µm	d99 µm
Ok Tedi copper concentrate	4.4	25	46	78	105
Century zinc concentrate	4.1	3.3	7.5	14	21
Century lead concentrate	4.8	10	20	33	47
Antamina copper concentrate	4.2	50	70	110	150
Antamina zinc concentrate	4.0	38	85	130	175
Whyalla magnetite concentrate	4.93	15	32	57	80

Table 4 compares relevant concentrate slurry data.

Table 4

	Typical Conc. (wt%)	Slurry Density (kg/m^3)	Yield stress (Pa)	Plastic Viscosity (mPas)
Ok Tedi copper concentrate	57.5	1800	1.56	9.74
Century zinc concentrate	35	1360	1.0	4.0
Century lead concentrate	37	1410	0.5	3.5
Antamina copper concentrate	63	1920	3.0	12
Antamina zinc concentrate	63	1890	3.0	13
Whyalla magnetite concentrate	55	1780	0.6	4
	60	1917	1.3	5.5
	65	2075	3.6	8

4. PREDICTED DEPOSIT VELOCITIES COMPARED WITH OPERATING VELOCITIES

Predicted deposit velocities in the four concentrate pipelines will now be compared with the operating velocities. The prediction methods are the same as discussed in Section 2 (Thomas, 2019) except that for simplicity, the d80 particle size is used as a representative size in the heterogeneous predictions and in the predictions of Sanders et al (2004). Table 5 shows the predicted Vd and Transition Velocities, Vt. These can be compared with the operating velocities in the largest ID pipe from Table 2.

The right column in Table 5 shows the velocity margin between the operating velocity and the highest predicted deposit velocity.

The Century pipeline has the lowest velocity margins. This is consistent with the very fine particle size of the Century concentrates and the lowest operating velocity.

The Ok Tedi velocity margins could be considered "standard" in that, in the early long distance concentrate pipelines, a velocity margin of 1 ft/s (i.e. 0.3 m/s) was generally adopted.

The Antamina velocity margins are higher than Ok Tedi, reflecting the larger pipe diameter, and also probably because there is so much head to dissipate anyway.
The Whyalla pipeline has the capacity to transport a range of concentrations over a relatively wide range of flow rates so the velocity margins range from 0.21 m/s to 0.86 m/s

Table 5

Comparing Predicted Deposit Velocities with Operating Velocities
(The Operating Velocities apply to the largest pipe ID)
The highest predicted Vd for each pipeline is shown in **Bold**

Concentrate Pipeline	Conc. (wt%)	Vdhet (m/s)	Vdvsl Thomas (m/s)	Vdvsl Sanders (m/s)	Vdt =Vt (m/s)	VOperate (m/s)	Velocity Margin (m/s)
Ok Tedi	57.5	0.34	0.85	**0.90**	0.74	1.22/1.26	0.32/0.36
Century Zn	35	<0.1	**0.86**	0.75	0.68	1.14	0.28
Century Pb	37	<0.1	**0.89**	0.81	0.47	1.14	0.25
Antamina Cu	63	0.67	0.90	**1.10**	0.99	1.66	0.56
Antamina Zn	63	0.84	0.90	**1.17**	1.00	1.66	0.49
Whyalla magnetite	55	0.40	0.75	**0.79**	0.46	1.36/1.65	0.57/0.86
	60	0.36	0.79	**0.85**	0.65	1.36/1.65	0.51/0.80
	65	0.32	0.83	0.90	**1.04**	1.36/1.65	0.21/0.61

Note that of the eight different concentrates and concentrations in Table 5, transition deposition determines the deposit velocity in only one case (Whyalla 65% concentration). In the other seven cases viscous sub-layer deposition determines the deposit velocity.

5. SOME SPECIFIC DESIGN ISSUES

5.1 CENTURY ZINC CONCENTRATE – ENTRAINED AIR IN SLURRY INFLUENCES RHEOLOGY

The Century zinc concentrate is beneficiated using froth flotation. Because of the very fine particle size of the Century zinc concentrate (see Figure 5), the Century zinc concentrate slurry contains a considerable amount of air in the form of micro-bubbles attached to the solid particles. These micro-bubbles are very tenacious and difficult to remove. Thus, typically there might be 20% air in the slurry prior to entering the pumps. Once the slurry passes through the centrifugal charge pump and the mainline pumps, all the air is compressed and dissolved in the water.

But it is not possible to measure the rheology of a fully dissolved slurry under such pressure. Hence, it is necessary to measure the rheology of a sample containing micro-bubbles at atmospheric pressure and adjust the results. This adjustment was discussed by Thomas et al (2019). At atmospheric pressure, the micro-bubbles are assumed to increase the yield stress and the plastic viscosity in a similar manner as would 20% volume concentration of spheres. The method of adjustment assumes both yield stress and plastic viscosity increase as per Eqn 1 below which was shown by Thomas, 2010 to approximate the well-known equation of D.G. Thomas (1965).

$$\text{Ratio Increase} = \exp(2.7\ Vr) \quad (1)$$

where Vr = Volume Ratio = Cv/(1-Cv)

So, for 20% air, Vr = 0.25 and the ratio increase is 1.96, or approximately 2. Hence at Cw= 35%, the measured rheology would have been Yield stress = 2.0 Pa and Plastic viscosity = 8 mPas. Dividing each by 2 we get the Yield stress = 1 Pa and Plastic viscosity = 4.0 mPas which are relevant to flow in the pipeline as shown in Table 4.

Operationally, the entrained air also causes some difficulties in flow measurement at the terminal. The air starts coming out of solution about 15 kms from the terminal and by the time it has arrived at the terminal, the turbulent flow has transformed it from micro-bubbles to slugs of air. These distort the magnetic flow meter reading.

5.2 WHYALLA MAGNETITE – EFFECT OF DEMAGNETISING

Prior to the pumps at the Whyalla pump station, the magnetite concentrate slurry flows through a de-magnetising coil. This has the effect of reducing the yield stress but has little effect on the plastic viscosity - compare Figures 6 and 7. Figure 6 shows a typical reduction in yield stress. The yield stress is about halved, which equates to about a 4% shift in concentration.

According to Wilson and Thomas (2006), the transition velocity, Vt, is given by:

$$Vt = 25\ (\text{Yield stress, Pa} / \text{Slurry density, kg/m}^3)^{0.5} \quad (2)$$

Consider Figure 6. Prior to de-magnetisation, the yield stress of magnetised slurry at Cw=65% is 10 Pa. For solids SG=4.93 the slurry density is 2075 kg/m^3 and Eqn 2 gives Vt = 1.74 m/s. This Vt exceeds the maximum operating velocity, so magnetised slurry at Cw=65% cannot be pumped. However, after de-magnetising, Figure 6 shows the yield stress reduces to 4.3 Pa and Eqn 2 gives Vt = 1.14 m/s which is less than the 1.36 m/s minimum operating velocity and so, once the slurry is de-magnetised the Cw=65% slurry can be pumped. Without de-magnetising, Figure 6 indicates the maximum concentration would be limited to Cw=60%.

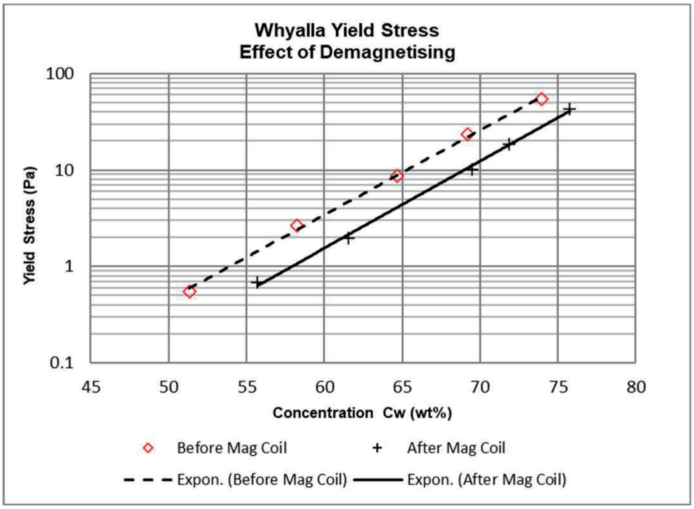

Figure 6

Figure 7 shows that de-magnetisation has little effect on the Plastic Viscosity.

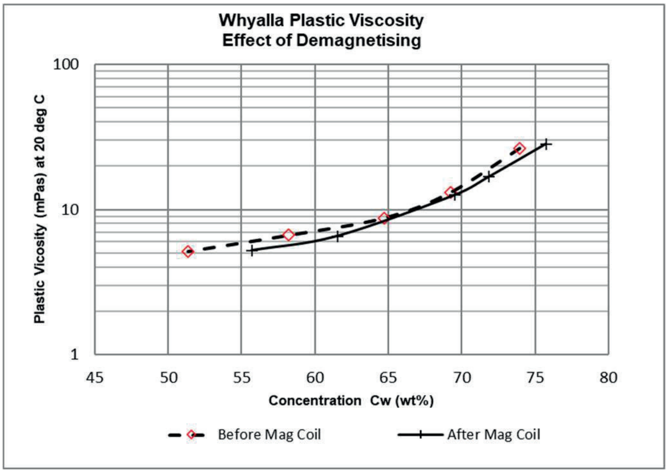

Figure 7

5.3 TRAIL-OUT IN WATER BATCHES AND PIPE WEAR

In 1991 pipe bottom wear was found to be occurring in the unlined Ok Tedi pipeline. Venton and Boss (1996) analysed this in detail and found that it was caused by corrosion-erosion in the trail-out of coarse solids in the frequent water batches used to separate slurry batches in the early years. Corrosion was exacerbated because the water in the water batches was rarely de-oxygenated. The present author carried out extensive on-site tests on trail-out in the Ok Tedi pipeline in 1992 as input into the Venton-Boss study. It was found that typically the concentration at the tail of a slurry batch decreased to a few percent within 20 to 30 minutes by which time the density and viscosity are essentially as for water.

For the Ok Tedi d80=46 microns particle size slurry, Table 5 shows the predicted critical Vd being Sanders et al (2004) Vdvsl=0.90 m/s. However, once a water batch follows a slurry batch into the pipeline, turbulent mixing at the slurry/water interface results in progressive trail-out of the solids into the following water batch. The finest particles will not trail-out too much since they can still be turbulently suspended even in water. But the coarser particles will not be able to be fully suspended in water and will settle and bounce or slide along the bottom of the pipe at a slower velocity. Some may even become stationary on the bottom of the pipe until being picked up by the following slurry batch.

Thomas et al (2002) compared trail-out in the Century and Antamina pipelines as shown in Figure 8 taken from that paper.

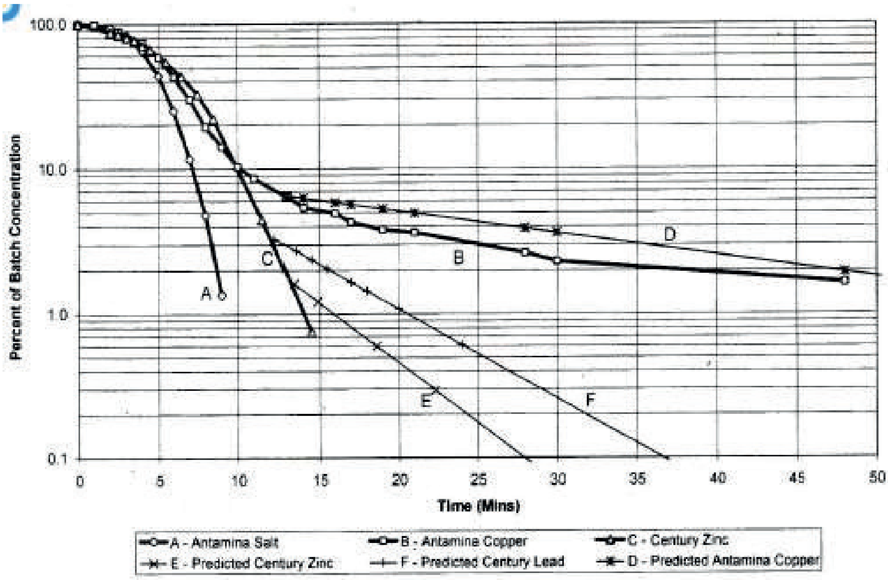

Figure 8

Figure 8 shows the decrease in concentration at the end of a batch as it enters the terminal. Even with homogeneous fluids, interfacial mixing occurs at the batch interface and knowledge of this interface is used extensively when batching different products in oil pipelines. During commissioning of the Antamina pipeline, a number of salt slugs were injected into the pipeline when pumping water. Curve A shows the decrease in salt concentration at the tail of a salt slug as it entered the terminal.

For typical slurries, there are two distinct trail-out phases. In the first 10 minutes the concentration decreases to about 10% of the original concentration. This phase is related to interfacial mixing and is of similar shape as the salt curve A. The second phase is dependent on particle size and involves the trailing of the coarser particles along the bottom of the pipe. Curve B shows data for Antamina copper concentrate and shows a flat exponential decay down to 2% after 50 minutes. With Century zinc concentrate being much finer, the Curve C data appears to remain in the interfacial mixing zone right out to the end of the test when the concentration is reduced to just 0.6% of the original concentration. Thomas et al (2002) give a method of predicting slurry trail-out.

6. CONCLUSIONS

Fundamentally, there are three different types of deposition which can occur in a concentrate pipeline. These are: heterogeneous deposition, viscous sub-layer deposition and laminar-turbulent transition deposition. The following deposit velocity prediction methods have been used in this study:

- Heterogeneous deposit velocity (Vdhet), is predicted using the Modified Wilson and Judge method of Thomas (2015).
- Viscous sub-layer deposit velocity (Vdvsl), is predicted by two methods: Thomas (1979b) and Sanders et al (2004).
- Transition deposit velocity (Vdt), is predicted using Wilson and Thomas (1985).

Four long distance concentrate pipelines have been considered and for each concentrate, deposit velocities have been predicted using the above four different methods. The results are shown in Table 5. For each concentrate, the highest predicted deposit velocity (shown in bold) is the critical one to be compared with the operating velocity. Of the eight different concentrates and concentrations in Table 5, transition deposition determines the deposit velocity in only one case (Whyalla 65% concentration). In the other seven cases viscous sub-layer deposition determines the deposit velocity.

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