22nd International Hydrotransport Conference
May 27th-30th, 2025, Prague, Czech Republic
ISBN 978-80-01-07404-6

# The Savage River magnetite pipeline utilises turbulent pressure gradient reduction of Bingham plastics

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**ABSTRACT**

The 85 km long Savage River magnetite concentrate pipeline in Tasmania, Australia was commissioned in 1967, and is still operating more than 57 years later. The normal magnetised concentrate exhibits Bingham plastic properties. De-magnetising reduces the yield stress, thereby lowering the transition velocity, allowing higher concentrations to be pumped. But higher concentrations mean higher pressures within the ageing pipeline. As a result, in recent years the operators have found it preferable to pump the normal magnetised slurry and take advantage of the turbulent pressure gradient reduction just above transition, as predicted by Wilson and Thomas (1), (2) and Thomas and Wilson (3).

## 1 INTRODUCTION

The Savage River iron ore mine is in the north-west region of the island state of Tasmania, Australia. From the mine, magnetite concentrate is pumped through an unlined steel slurry pipeline, 85 km north to Port Latta. The Savage River pipeline was commissioned in 1967. In (4), Norm Cowper, who was pipeline superintendent at the time, relates some of the drama during commissioning with attempts to restart the shutdown pipeline.

The 57 years of successful operation of this unlined steel pipeline is a tribute to the operators over the years adhering to the required pH control by addition of lime. This has been improved by two local innovations. Firstly, purposely over-liming in excess to that required for pH control results in a scale buildup which further protects the steel from exposure to the slurry. Secondly, the thickness of the scale is controlled by regular pigging (currently every two weeks). Pigging has been enhanced by the local development of a special pig, which as well as removing excess scale, also polishes the inside of the pipe. These two innovations are described by Frank Salt in (5). In March 2020, water pumping tests three days after pigging gave a pipeline roughness of 0.03 mm, which is less than the 0.05 mm roughness of new steel pipe.

The concentrate is naturally magnetised which results in a Bingham plastic rheology. Magnetism influences the yield stress but not the plastic viscosity. For example, demagnetising by piping the slurry through a demagnetising coil can reduce the yield stress to 0.38 of the original but cause no change in the plastic viscosity. This results in some interesting slurry hydraulic differences between magnetised and demagnetised slurry.

For the same solids concentration and flow rate, magnetised slurry will have a lower turbulent pressure gradient than demagnetised slurry because of non-Newtonian effects relating to the higher yield stress. The lower pressure gradient is predicted using (3). The Savage River pipeline currently utilises this effect by pumping the higher yield stress magnetised slurry rather than demagnetised slurry. However, under certain circumstances there are advantages in pumping demagnetised slurry instead. The advantages and disadvantages of these two slurry types are discussed in this paper by comparing pipeline hydraulic predictions and operational experience. Note: In this paper, a demagnetised slurry is a slurry with a reduced yield stress but not zero yield stress.

## 2 PIPELINE DETAILS

The pipeline is constructed from API 5L X52 DN225 steel pipe with OD 244.5 mm. The original pipe wall thicknesses were 13.84 mm, 11.13 mm, 9.35 mm, and 6.35 mm. The pipeline was designed with a design factor of 0.72 applied to the steel yield stress as per the oil and gas pipeline codes at the time. It is estimated that over the 57 years of operation an average steel wall thickness of about 1.5 mm has been lost due to corrosion, mainly through pitting.

For pipeline hydraulic predictions the following pipe ID assumptions have been adopted based on a two weekly pigging regime. It is assumed that two weeks after pigging, 1.5 mm thickness of scale has formed on the inside of the pipe. This equals the 1.5 mm steel lost to wear so that just before the next pigging the pipe ID is the same as for new pipe All predictions in this paper, apart from those in Section 6, are based on IDs just before pigging, i.e. the same ID as new pipe. Pigging is assumed to remove 1 mm of scale making the IDs 2 mm larger than new pipe. Table 1 gives the assumed pipe IDs

**Table 1: Pipe OD 244.5 mm. Assumed pipe IDs before and after piggin**

| | New pipe wt & ID 13.84 mm (216.8) | New pipe wt & ID 11.13 mm (222.2) | New pipe wt & ID 9.35 mm (225.4) | New pipe wt & ID 6.35 mm (231.8) |
|---|---|---|---|---|
| Before pigging | 216.8 | 222.2 | 225.4 | 231.8 |
| After pigging | 218.8 | 224.2 | 227.4 | 233.8 |
| Average IDs | 217.8 | 223.2 | 226.4 | 232.8 |

A pipe roughness of 0.03 mm is assumed as described in Section 1 above. For pipeline Maximum Allowable Operating Head (MAOH) 1.5 mm of steel wall thickness loss is assumed with a 0.80 Design Factor as per the current Slurry Pipeline Code.

## 3 MAGNETITE SLURRY RHEOLOGY

The solids SG of Savage River concentrate varies slightly but SG=5 is used in this paper. The particle size distribution of the Savage River concentrate is typically about 80% minus 45 microns and less than 0.6% plus 106 microns.

Magnetite slurries can be described as Bingham plastics for which a straight line is fitted to the high shear rate data. The slope of the line equals the plastic viscosity and the intercept on the shear stress axis is the yield stress. When normal magnetite slurry is passed through a demagnetising coil, the yield stress decreases but the plastic viscosity remains relatively constant. This is illustrated in Figure 1 which compares viscometer measurements at nominal Cw=64.1% for a magnetised slurry and demagnetised slurry tested in 2020. Demagnetising reduced the yield stress to 0.38 of the normal yield stress whereas the plastic viscosity remains essentially the same.

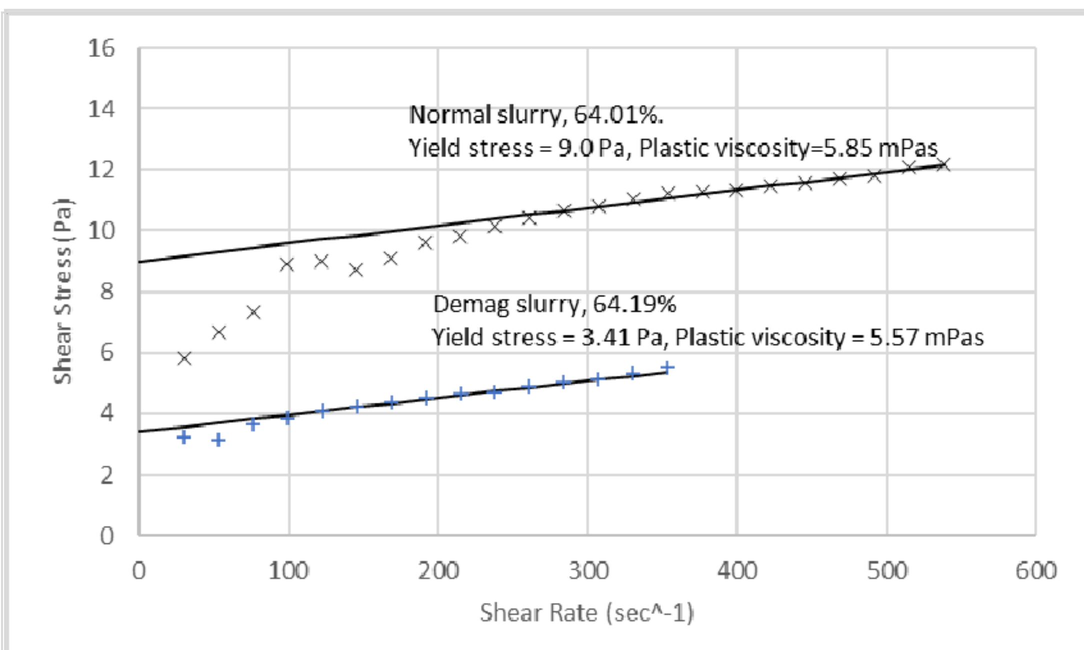


**Figure 1: Rheograms for normal and demagnetised slurry at nominal Cw=64.1%**

Note: The demagnetised slurry, although referred to as "demagnetised", may not be fully demagnetised since Slurry Systems Engineering Pty Ltd (SSE) has often found that passing a demagnetised sample through a laboratory demagnetising coil, further reduces the yield stress. In fact, it may not be possible to fully demagnetise a magnetite slurry.

Over the period from 2008 to 2020, SSE, completed a range of rheology tests in SSE's laboratory on different magnetite slurry samples provided by Grange Resources. In addition to rheology testing, in early 2020 SSE was engaged in a major investigation for Grange Resources which included a site visit and water tests on the pipeline. Figure 2 shows all yield stress results for normal magnetised and demagnetised samples over a range of concentrations.

The top line, Y = 7.784E-6 exp(0.2178 Cw), fits the 2020 magnetised sample yield stress data. All other magnetised data also cluster around this line except for the 2018 sample data. Equation 1 is adopted for magnetised yield stress in this paper.

$$\text{Yield Stress (magnetised), (Pa)} = 7.784E\text{-}6 \exp(0.2178\ Cw) \quad (1)$$

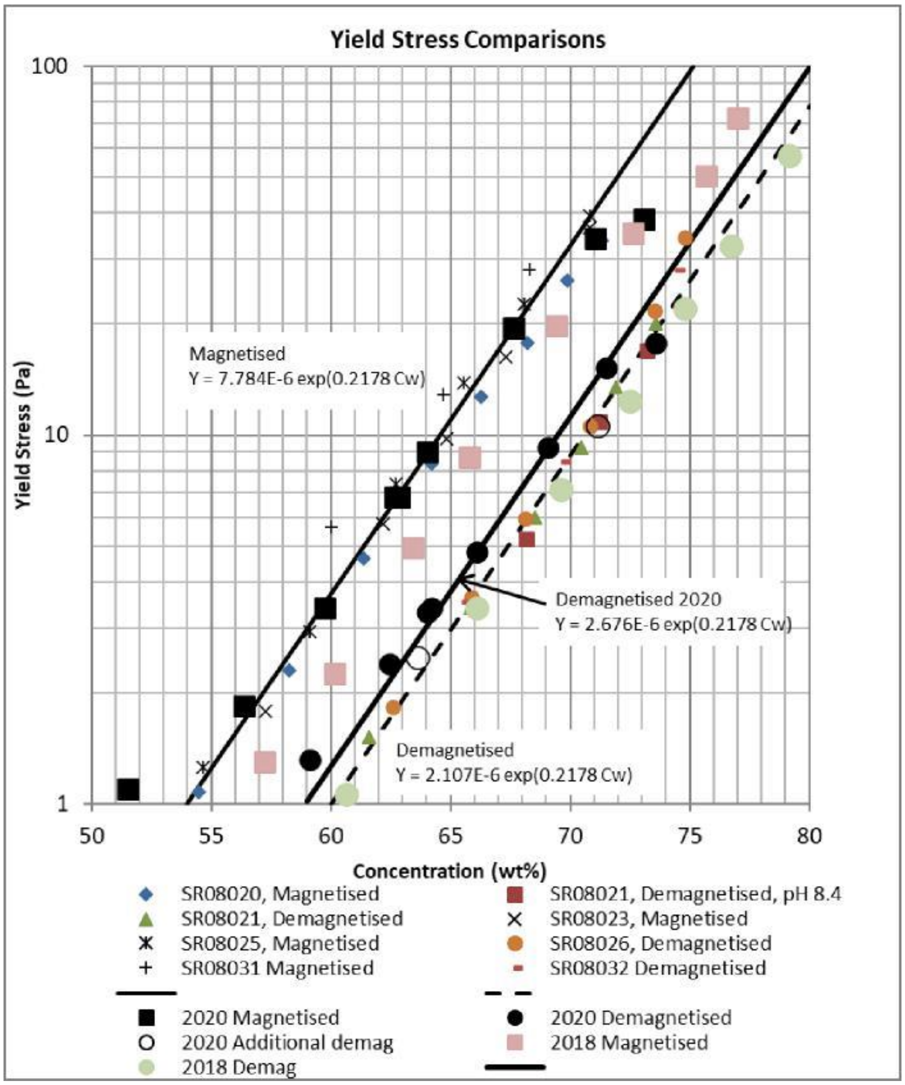


**Figure 2: Correlation of measured yield stress of all samples from 2008 to 2020**

The middle line, Y = 2.676E-6 exp(0.2178 Cw) fits the 2020 demagnetised data. Most other demagnetised data are better described by the slightly lower line, Y = 2.107E-6 exp(0.2178 Cw). However, the 2020 equation is adopted for demagnetised yield stress in this paper.

$$\text{Yield Stress (demagnetised), (Pa)} = 2.676E\text{-}6 \exp(0.2178\ Cw) \quad (2)$$

Figure 3 shows all magnetised and demagnetised plastic viscosity data measured over the period 2008 to 2020. As was illustrated in relation to Figure 1, demagnetising reduces the yield stress but has essentially no effect on the plastic viscosity. This is confirmed in Figure 3 in which all plastic viscosity data below Cw=70%, both magnetised and demagnetised, from 2008 to 2020 are essentially described by Equation 3:

$$\text{Plastic viscosity, (mPas)} = 0.2717 \exp(0.0528\ \text{Cw}) \tag{3}$$

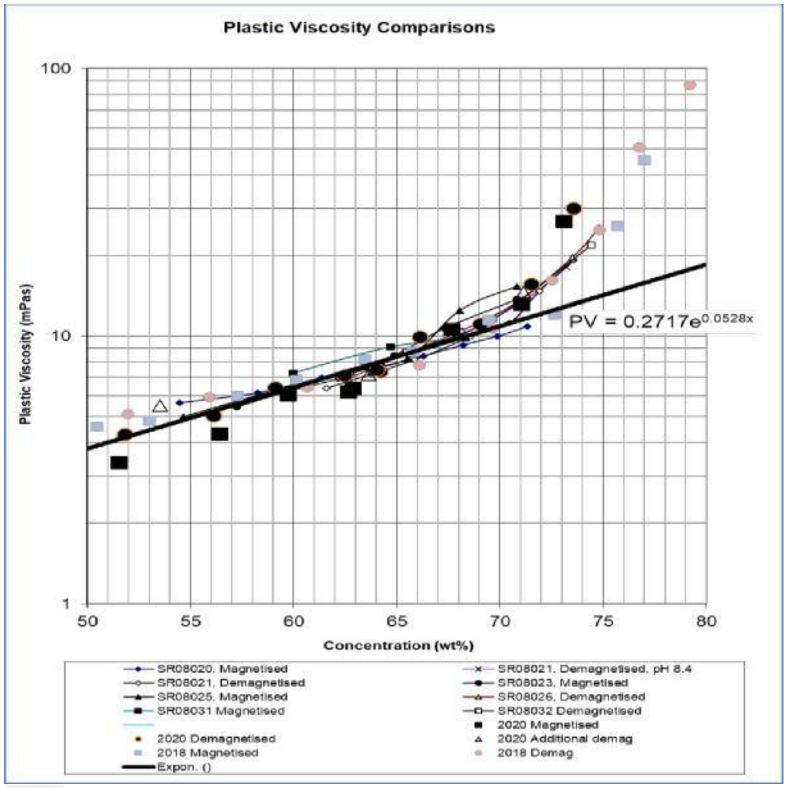


**Figure 3: Correlation of measured plastic viscosity of all samples from 2008 to 2020**

## 4 NON-NEWTONIAN PRESSURE GRADIENT EFFECTS

### 4.1 Comparing magnetised and demagnetised pressure gradients

Magnetite slurries are Bingham plastics and therefore exhibit non-Newtonian effects in turbulent flow. This is illustrated in Figure 4 which shows predicted turbulent flow pressure gradients in the thinnest wall (231.8 mm ID) pipe for magnetised slurry at Cw=63.5% (yield stress 7.90 Pa, plastic viscosity 7.77 mPas) and demagnetised slurry (yield stress 2.72 Pa, plastic viscosity 7.77 mPas). Predictions utilise the non-Newtonian theory (1),(2), which is based on enhanced turbulent microscale and associated viscous sub-layer thickening. For a Bingham plastic, the thickening of the viscous sub-layer results in a reduction in the turbulent pressure gradient compared with a Newtonian fluid with a viscosity equal to the Bingham plastic viscosity but zero yield stress. This was further discussed and illustrated in (3).

For the pressure gradient comparisons in Figures 4 and 5, a pipe roughness of 0.01 mm is assumed. The flatter curves at the lower velocities indicate laminar flow. According to (2),(3) the transition velocity for Bingham plastic pipe flow is given by Eqn 4. With yield stress in Pascals and slurry density in kg/m$^3$, Vt is in m/s.

$$\text{Transition velocity (Vt)} = 25\ (\text{yield stress/slurry density})^{0.5} \tag{4}$$

The transition velocities between turbulent flow and laminar flow are given by Eqn 4 as 1.56 m/s for the magnetised slurry and 0.91 m/s for demagnetised slurry.

The upper dashed line in Figure 4 shows the predicted pressure gradient for the same viscosity of 7.77 mPas but zero yield stress, i.e. a Newtonian fluid. So, at velocities above 1.6 m/s the three upper curves, which are all for the same 2033 kg/m$^3$ slurry density and 7.77 mPas viscosity, illustrate the reduction in turbulent flow pressure gradient as the yield stress is increased from zero to 7.90 Pa. Incidentally, the transition velocity for the zero yield stress slurry occurs when Reynolds Number = 2000, which in this case equates to a transition velocity of just 0.033 m/s.

At the typical 8270 tonnes per day (tpd) solids throughput, the flow rate at Cw=63.5% is 267 m$^3$/h, giving a velocity of 1.76 m/s in the 231.8 mm ID pipe. At V=1.76 m/s the predicted pressure gradient of the magnetised slurry is 185 kPa/km and 216 kPa/km for the demagnetised slurry. i.e. because of non-Newtonian effects, the turbulent pressure gradient of the magnetised slurry is 14% lower than the demagnetised slurry. Thus, if pumping at a particular concentration (63.5%) there is an advantage in pumping magnetised slurry rather than demagnetised slurry. Note, however, the 1.76 m/s operating velocity is only 0.2 m/s above the 1.56 m/s transition velocity for the magnetised slurry, which is a minimum margin.

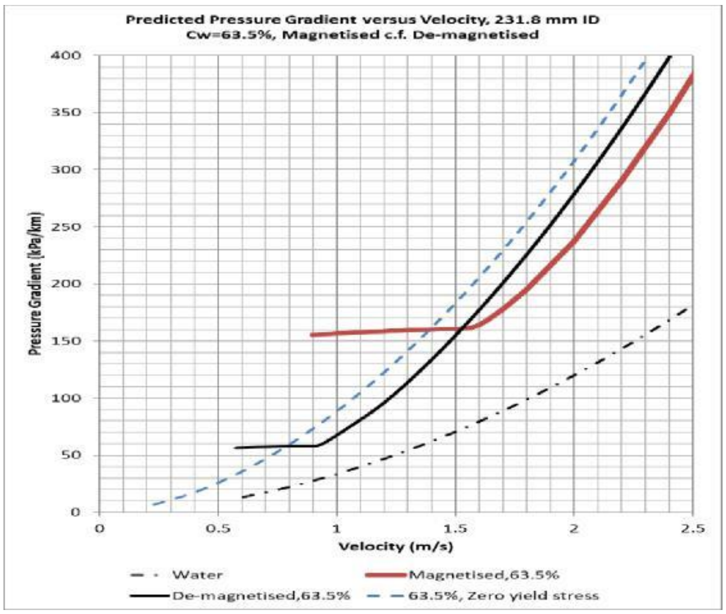


**Figure 4: Effect of changes in yield stress on pressure gradient**

Figure 4 provides an example of the advantages in pumping magnetised slurry to achieve a lower pressure gradient. But there are other issues which may make pumping demagnetised slurry preferable. Because the transition velocity is lower for the demagnetised slurry, the slurry can be pumped at lower velocities while still maintaining turbulent conditions. Therefore, the same 8270 tpd solids can be achieved by pumping at a lower velocity and a higher concentration.

Consider Figure 5 which shows operating data points at 8270 tpd solids throughputs for demagnetised slurries at Cw=63.5%, 66%, 67% and 68% in a 231.8 ID pipe. Firstly, consider increasing the demagnetised slurry Cw to 66%. The operating velocity is reduced from the 1.76 m/s at Cw=63.5% to 1.63 m/s and the pressure gradient is reduced to 182 kPa/km which is slightly less than the 185 kPa/km applying to magnetised slurry at Cw=63.5%. From Eqn 4 the transition velocity is 1.18 m/s, well below the 1.63 m/s operating velocity. These numbers suggest that demagnetised slurry at Cw=66% may be a viable alternative to the current magnetised Cw=63.5% slurry.

A further increase to Cw=67% demagnetised slurry gives an operating velocity of 1.57 m/s which is only 0.27 m/s above the transition velocity, so Cw=67% is the maximum possible demagnetised concentration. The pressure gradient has reduced to 170 kPa/km. So, pumping demagnetised slurry at Cw=66% and 67% are two potential pumping options.

Note: In a recent paper (6), heterogeneous and viscous sub-layer deposit velocities (Vdhet and Vdvsl respectively) were predicted for four long distance concentrate pipelines. Similar predictions for the current magnetised slurry at Cw=63.5% give Vdhet = 0.21 m/s and Vdvsl = 0.84 m/s, both well below the 1.56 m/s transition velocity, and for the demagnetised Cw=67% slurry, Vdhet = 0.17 m/s and Vdsl = 0.85 m/s, also well below the 1.30 m/s transition velocity. Hence these Vdhet and Vdvsl predictions, which are based on turbulent flow conditions, do not apply and the actual deposit velocity coincides with the transition velocity.

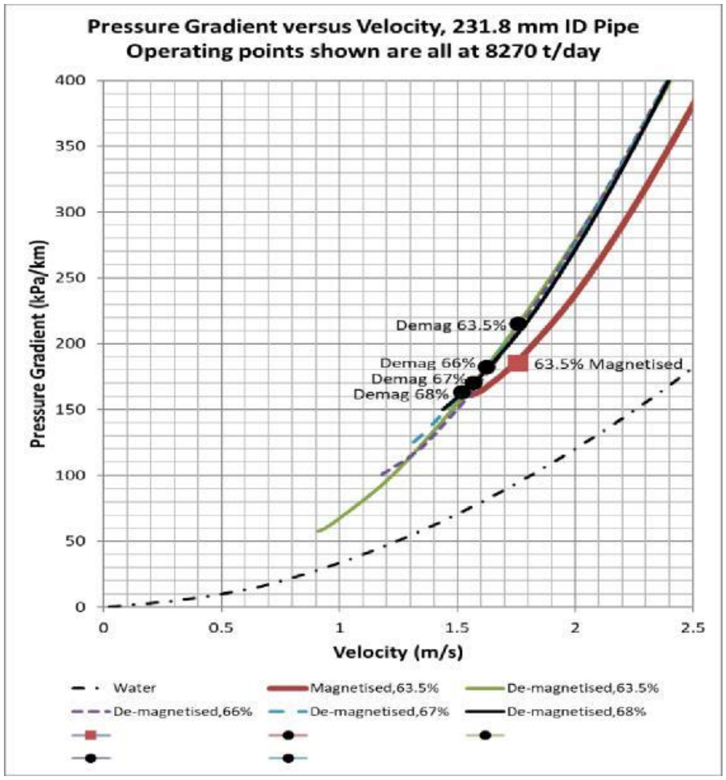


**Figure 5: Demagnetised slurry at lower velocities, but higher concentrations, achieve same solids throughput**

## 5 HYDRAULIC GRADIENT LINES ON ROUTE PROFILE

### 5.1 Normal magnetised slurry, Cw=63.5%, Q=267 m$^3$/h (8270 tpd)

Figure 6 shows the predicted Hydraulic Gradient Line (HGL) on the Route Profile for magnetised slurry at 63.5% at a flow rate of 267 m$^3$/h (8270 tpd solids) with the pipe ID's at the minimum just before pigging. Pump pressure is 1791 psi (12,350 kPa). (Note: The original Wilson Snyder type of plunger pumps are still used and psi pressure measurement is retained). The HGL clears the ground RL at Km 80.3 by 20 m. The dashed HGL just below it is the predicted HGL immediately after pigging when the pipe IDs are at their maximum. In this case pump pressure reduces to 1687 psi. The dashed HGL clears the ground RL at Km 80.3 by 15 m. Also shown is the Maximum Allowable Operating Head (MAOH) for the varying pipe wall thicknesses based on a design factor of 0.80 as per the current Slurry Pipeline Code and assuming 1.5 mm steel wall thickness loss. The spikes in the MAOH are the short lengths of 13.85 mm wall thickness pipe, generally used under creek and road crossings.

The shutdown head is also shown as a horizontal dashed line. When a slurry pipeline is shutdown full of slurry, the terminal valve must be timed to close such that slurry is locked in the pipeline. If this was not done, slurry would drain out of the pipeline and also drain from high points down to valleys, making restart very difficult. The terminal valve is timed to close so as to provide a positive "shutdown head" throughout the pipeline. The shutdown head shown allows for 20 m clearance of the highest point. There is a resulting minimal 70 m margin between the MAOH and the shutdown head just before the terminal. It should be noted that Grange Resources are intending to install a valve at Km 50.2 to further reduce the shutdown head towards the end of the pipeline so as to provide a greater margin between the shutdown head and the pipeline MAOH.

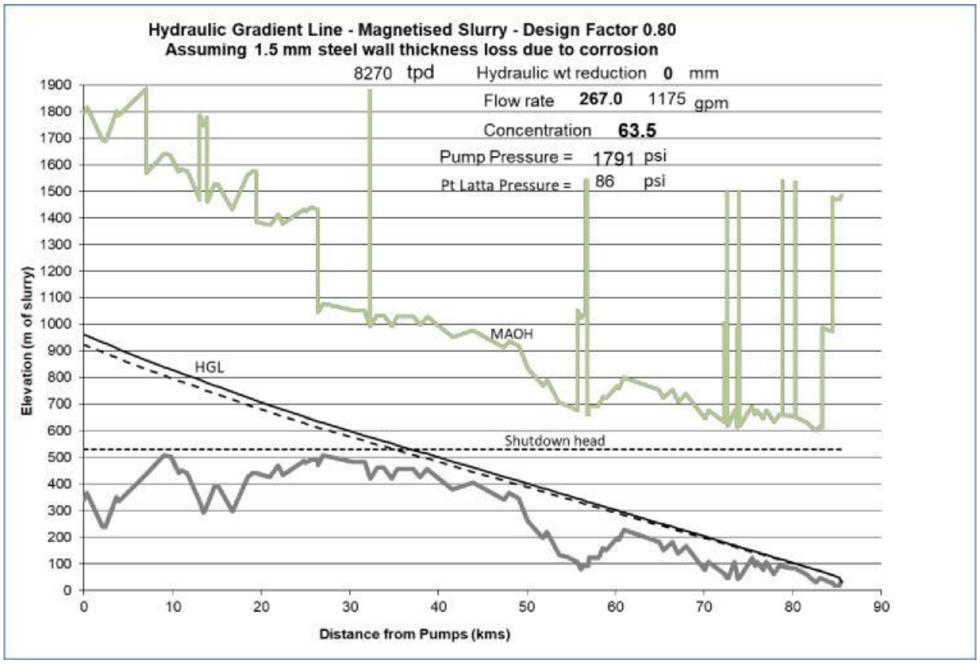


**Figure 6: Magnetised slurry at Cw=63.5%. Route profile, HGL, MAOH and shutdown head.**

### 5.2 Demagnetised slurry, Cw=63.5%, Q=267 $m^3/h$ (8270 tpd)

Figure 7 shows the predicted HGL on the Route Profile for demagnetised slurry at the same conditions (Cw=63.5%, Q=267 $m^3/h$, just before pigging). Pump pressure has increased to 2249 psi (15,500 kPa) which exceeds the maximum 2000 psi pump pressure. The HGL clears the ground profile at Km 80.3 by 30 m.

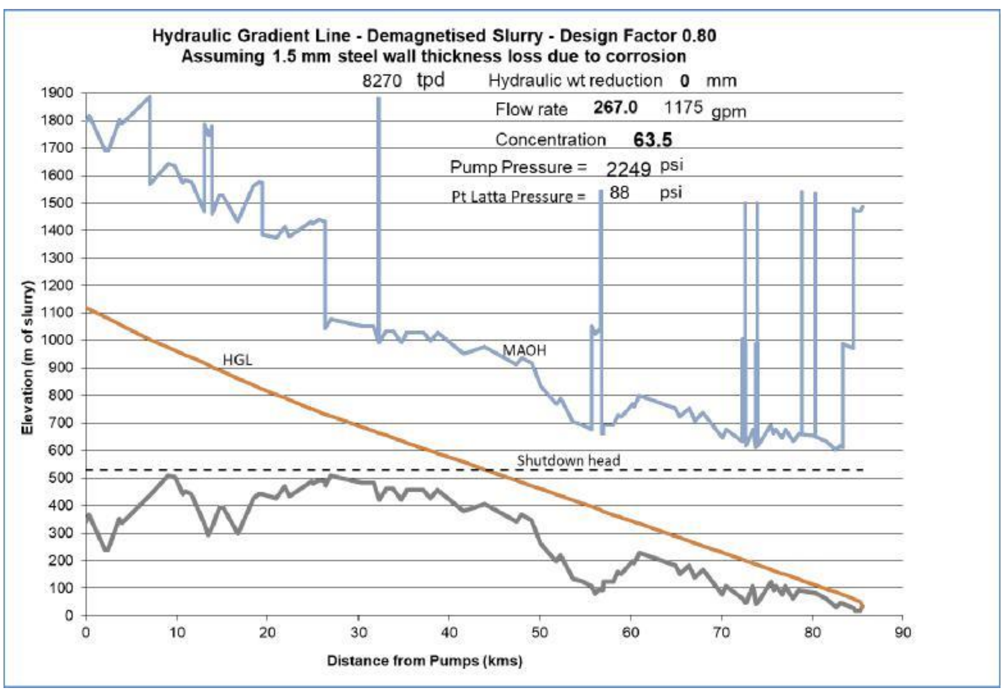


**Figure 7: Demagnetised slurry at Cw=63.5%. Route profile, HGL, MAOH and shutdown head.**

### 5.3 Demagnetised slurry at Cw=66%, Q=246 $m^3/h$ (8270 tpd)

Because of the lower yield stress of the demagnetised slurry, the operating velocity can be decreased. From earlier Figure 5, the velocity is 1.62 m/s in the 231.8 mm ID pipe which is well above the 1.18 m/s transition velocity for the demagnetised slurry at

Cw=66%. Figure 8 shows the predicted HGL on the Route Profile for demagnetised slurry at these conditions (Cw=66%, Q=246.4 $m^3$/h, just before pigging). Pump pressure has reduced to 1655 psi (11,400 kPa) from the 2249 psi (15,500 kPa) for demagnetised slurry at 63.5% in Figure 7 and is less than the 1791 psi (12,350 kPa) for the magnetised slurry at 63.5% in Figure 6. However, the HGL clearance at Km 80.3 is now reduced to 15 m with the smallest ID pipe just before pigging and just 10 m with the largest ID pipe immediately after pigging (HGL not shown). At Km 39 and Km 44 the HGL clearance is near zero in the largest ID pipe immediately after pigging (HGL not shown). Because of the higher slurry density, the margin between the minimum MAOH near the terminal and the shutdown head has reduced to 50 m compared with the 70 m at Cw=63.5%.

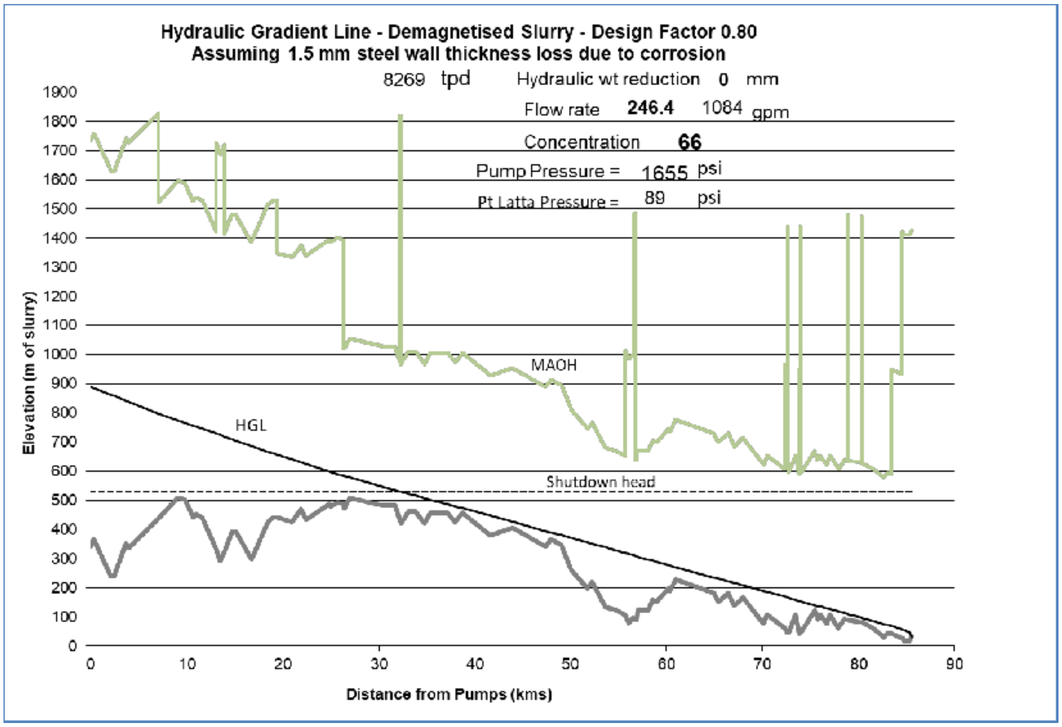

**Figure 8: Demagnetised slurry at Cw=66%. Route profile, HGL, MAOH and shutdown head.**

### 5.4 Demagnetised slurry at Cw=67%, Q=239 (8270 tpd)

In earlier Figure 5, Cw=67% demagnetised slurry is shown at a velocity of 1.57 m/s in the 231.8 mm ID pipe which is a minimum margin above the 1.30 m/s transition velocity for this slurry. Figure 9 shows the predicted HGL on the Route Profile for demagnetised slurry at these conditions (Cw=67%, Q=238.6 $m^3$/h, just before pigging). Pump pressure has reduced to 1475 psi (10,170 kPa) from the 1655 psi (11,400 kPa) for demagnetised slurry at 66% in Figure 8 and is less than the 1791 psi (12,350 kPa) for the magnetised slurry at 63.5% in Figure 6. However, there are now regions between Km 35 and Km 50 and around Km 80, where the HGL intersects the ground profile with the ground profile being at a steeper down slope than the HGL. In this situation, termed "slack flow", the slurry flows faster down the steeper slope as a partly filled pipe with water vapour in the top portion. Slack flow needs to be avoided since the higher velocities will increase erosive wear at the bottom of the pipe.

Also, the margin between the minimum MAOH near the terminal and the shutdown head is now reduced to 40 m compared with the 70 m at Cw=63.5%. It is concluded that for 8270 tpd solids throughput, demagnetised slurry at Cw=67% is not viable and demagnetised slurry is best pumped at a maximum Cw=66%.

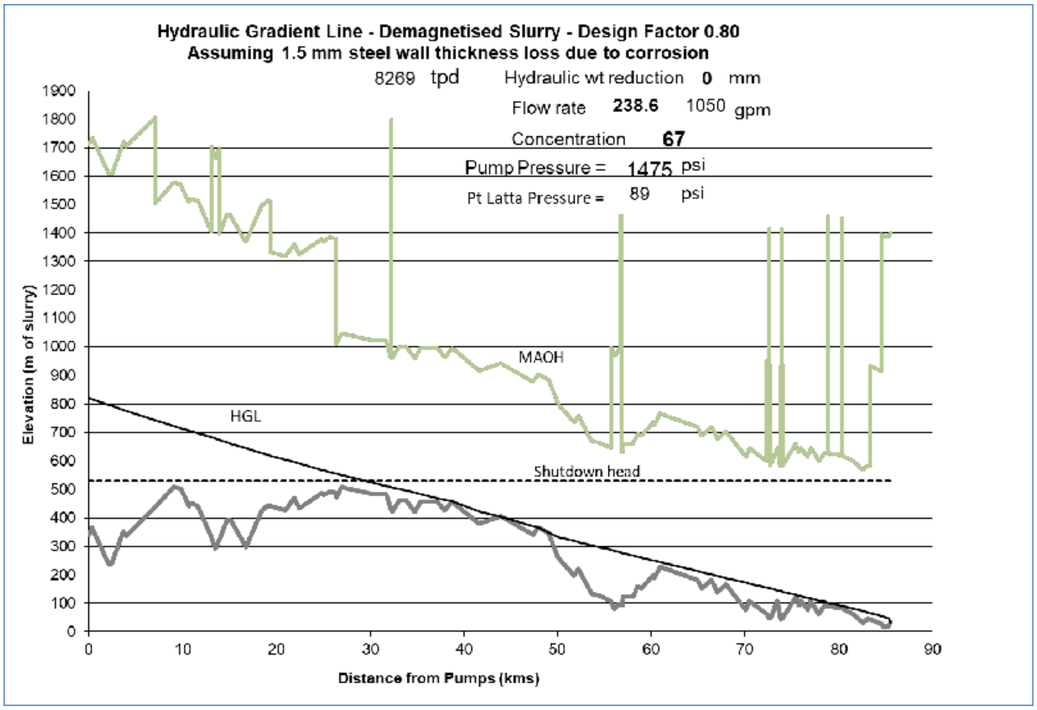


**Figure 9: Demagnetised slurry at Cw=67%. Route profile, HGL, MAOH and shutdown head.**

## 6 OPERATING ISSUES

### 6.1 Predicted pump pressure compared with observed

Table 1 in Section 2, gives the assumed pipe IDs before and after pigging. All pipeline predictions hitherto in this paper have been based on pipe IDs just before pigging, equal to new pipe IDs, as explained in Section 2. Below predictions based on IDs just before pigging, just after pigging and midway between pigging (average ID) are compared with some measured data.

Data provided for a steady, 21 hour period, pumping magnetised slurry at Cw=62.8%, flow rate 266.4 $m^3$/h, gave a measured pump pressure = 1629 psi (11,232 kPa). From Figures 2 and 3, yield stress=6.78 Pa and plastic viscosity=7.48 mPas. For these operating conditions, using SSE's prediction method as in this paper, and based on the average IDs in Table 1, the predicted pump pressure is 1702 psi, which is 4.5% higher than the measured pump pressure. Assuming the other Table 1 IDs, before pigging gives 1782 psi (+9.4%) and after pigging 1664 psi (+2.1%).

### 6.2 Pipeline restart

Although pumping magnetised slurry provides an easy to operate system, the magnetised slurry, perhaps surprisingly, is not as easy to restart after a shutdown as it is with demagnetised slurry. The reason why magnetised slurry at, for example, Cw=63.5%, is more difficult to start than demagnetised slurry, is probably because the operating velocity in the thinnest wall pipe is only 0.20 m/s above the transition velocity. This means that during restart, as the velocity is slowly increasing, there are likely to be extended periods of laminar flow before fully developed turbulent flow is restored. In contrast, from the discussion in Section 4.1, demagnetised slurry at Cw=66% at 1.63 m/s, achieves the same solids throughput at a slightly lower pump pressure. Importantly, with this demagnetised slurry, the 1.63 m/s operating velocity is 0.45 m/s above the 1.18 m/s transition velocity so there will be less periods of laminar flow as the velocity is increasing during restart.

### 6.3 Why is demagnetised slurry not pumped at present?

Demagnetised slurry has been pumped in the Savage River pipeline for much of its life. However, the last time the demagnetising coil stopped working and was eventually repaired, was in December 2019. During the changeover, both the flow rate and slurry concentration were kept constant at 267 $m^3$/h and Cw=64% respectively. Great difficulties were encountered during the subsequent changeover from magnetised to demagnetised operation and the changeover was eventually abandoned. Pump wet end valves and other parts had to be replaced. Since then it has been found simpler to just keep operating on magnetised slurry.

Figure 5 showed how, for the same flow rate and concentration, demagnetised slurry has a higher pressure gradient than magnetised slurry. During the changeover pump pressure slowly increased and approached the 2000 psi limit before the demagnetising coil was switched off. This increase in pump pressure as demagnetised slurry filled the pipeline is a direct verification of the pressure reduction of Bingham plastics predicted by (1), (2), (3).

As shown in Figure 5, the flow rate of demagnetised slurry must be decreased and the concentration increased to achieve the same solids throughput at the same pressure gradient as magnetised slurry. But the problem during a changeover in the pipeline is that reducing the flow rate to lower the pressure gradient of the demagnetised slurry in say the first half of the pipeline means that the velocity falls below the transition velocity in the last half of the pipeline filled with magnetised slurry. So, instead of the pump pressure decreasing as demagnetised slurry fills the pipeline at the lower flow rate, the pump pressure may actually increase because of bed formation in the last half of the pipeline filled with magnetised slurry.

Changing from magnetised to demagnetised slurry in an operating pipeline is not straightforward. This is especially the case with an ageing pipeline such as Savage River, with maximum pressure limitations. At present Grange Resources prefers to pump the magnetised slurry.

## 7 CONCLUSIONS

The Savage River pipeline currently pumps magnetised slurry at Cw=63.5%, taking advantage of the reduced turbulent pressure gradient due to non-Newtonian effects, as predicted by (1,2,3). The pipeline has been operated in the past with demagnetised slurry which has a lower yield stress, and the authors have shown how demagnetised slurry can be pumped at a lower flow rate and higher concentration to achieve the same solids throughputs at a slightly lower pump pressure. For example, in Section 5.3 demagnetised slurry at Cw=66% requires a lower pump pressure (1655 psi) compared with the normal magnetised slurry at Cw=63.5% (1791 psi). Demagnetised slurry at Cw=67% results in an even lower 1475 psi pump pressure but then slack flow issues occur making Cw=67% unviable. One disadvantage of demagnetised slurry at Cw=66% is that the higher slurry density reduces the margin between the minimum MAOH near the terminal, and the shutdown head, to about 50 m compared with 70 m for the current magnetised Cw=63.5% operation.

## ACKNOWLEDGMENTS

The authors thank Grange Resources for permission to publish this paper. We also thank Frank Salt for helpful discussions during the writing of the paper.

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