Design of the Sar Cheshmeh gravity flow tailings pipeline, Iran

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ABSTRACT

The design of a gravity flow tailings pipeline at the Sar Cheshmeh copper mine in Iran is described. The 4069 m long, DN 1050 steel pipe, gravity pipeline system, is designed to transport 3949 dry tonnes per hour of low concentration tailings to a paste thickener plant. The pipeline route traverses two valleys separated by a high point near the middle so the pipeline profile differs significantly from most gravity pipelines which typically flow continuously downhill.

The 32.2 m elevation difference between pipeline entrance and exit exceeds the 10.9 m head required for the average slurry flow so slack flow typically exists in the first few hundred metres of the pipeline. The use of fixed chokes to minimise slack flow was not an option because excess head difference is required during flushing of the pipeline. To accommodate the slack flow, the initial 310 metres of the pipeline consists of rubber mine hose following an S-shaped route down the 15% slope from the screen box.

The pipeline commenced operation in 2012 and is currently (first seven months of 2016) transporting tailings at an average 76,700 tonnes per day, equivalent to an average rate of 28 Mtpa of tailings.

1. INTRODUCTION

The National Iranian Copper Industries Company's Sar Cheshmeh copper mine in Kerman province Iran, has been operating since 1980. Until recently the minus 0.3 mm tailings were transported from the Concentrator at 38% to 45% concentration by weight via a gravity channel 17 km to a traditional tailings dam.

To reduce the height of the required embankment wall for the expansion of the tailings storage facilities and also reduce the quantity of evaporation loss and hence achieve more water recovery, ATC Williams proposed a thickened tailings deposition scheme which involves additional thickening to 59% to 61% w/w concentration using paste thickeners. The paste thickeners are located at the head of the tailings deposit beach, 8.5 kms from the main tailings embankment. Thickened tailings, discharged from the paste thickeners, flow towards the tailings dam, forming a sloped deposit, with the yield stress of the thickened tailings determining the tailings beach slope. This design minimised the additional retaining dam wall height required to accommodate future mine production and provided an overall lower cost when compared with continuing the existing (lower concentration) tailings storage regime with its high dam costs.

The paste thickeners are fed by a 4069 m long, DN 1050 steel pipe, gravity pipeline which commences with a channel flow diversion located 3.5 kms from the Concentrator. The pipeline route profile includes two valleys separated by a high point near the middle so it was not feasible to use a channel to transport the low concentration tailings from the existing channel across to the paste thickeners. The high point between the valleys is at elevation (EL) 2428.5 which is just 0.7 m higher than EL at discharge. The pipeline route is therefore very much different than most gravity pipelines which typically flow continuously downhill.

Figure 1 shows a general plan of the SCM Concentrator, tailings channel and gravity pipeline to the Paste Thickeners.

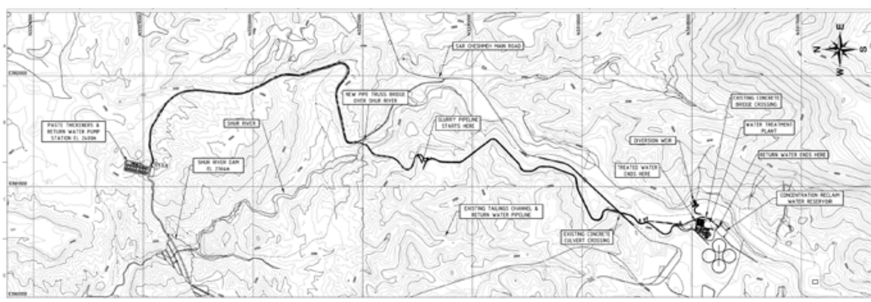

Figure 1 General plan of the SCM concentrator, tailings channel and gravity pipeline to the Paste Thickeners

2. BASIS OF HYDRAULIC DESIGN

2.1 Design throughput

The design solids throughput is 3,949 tph, which includes a 15% margin. Based on a solids SG of 2.80 the resulting design volume flow rates range from 7854 m^3/h at Cw=38% to 6237 m^3/h at Cw=45%. It will be seen in Section 5 that the Operating Envelope actually spans a much larger range of both solids throughput and concentration.

2.2 Route profile

The route profile is shown in Figure 2. The elevation of the pipe invert at the start of the pipeline is the same elevation as the bottom of the screen chamber, EL 2460. The screens in the screen chamber are 3.8 m above the invert of the inlet pipe, i.e. at EL 2463.8. The discharge elevation into the paste thickeners distribution box is at EL 2427.8. The high point between Chn 1,400 to 1,550 was excavated to a depth of 1.94 m to reduce the elevation from EL 2430.4 to EL 2428.5, so this high point around Chn 1500 is just 0.7 m higher than the discharge EL into the paste thickeners.

Excluding the vertical discharge riser into the paste thickeners, the maximum pipeline slope is 16%.

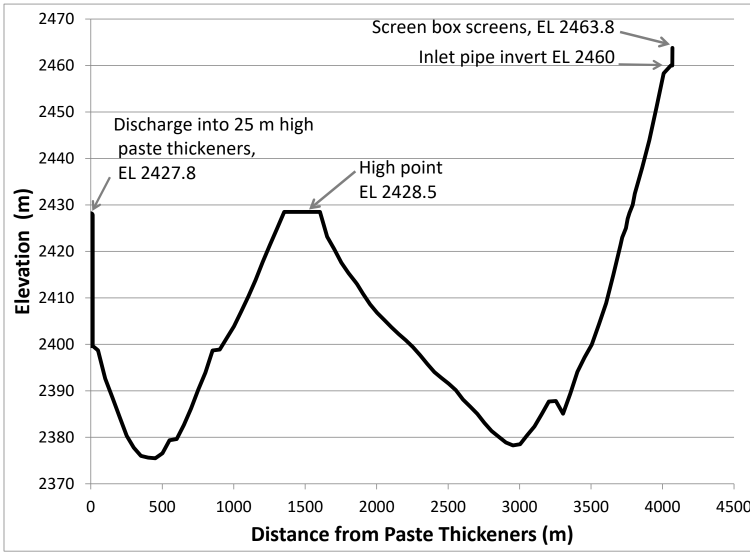

Figure 2 Pipeline route profile

2.3 Selected pipe

The pipeline is constructed using DN 1050 steel pipe, OD 1067 x 12.7 wt, API 5L X52 grade. The ID is 1042 mm.

Under normal operating conditions, slack flow will exist over part of the initial 310 m of the pipeline. The slack flow section will experience high pipe wear rates and rubber mine hose was selected in the slack flow section.

2.4 Particle size and solids SG

The particle sizing is shown in Figure 3. p_{99} = 280 μm, p_{80} = 120 μm, p_{50} = 40 μm. The design solids SG=2.80.

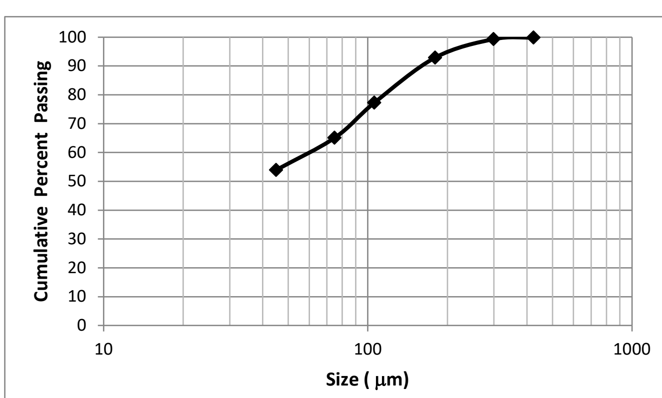

Figure 3 Particle Size

2.5 Slurry rheology

Slurry rheology was measured using a Contraves RM115 rotational viscometer. Shear stress versus shear rate plots are shown in Figure 4. Straight lines are shown fitted to the high shear rate data to give the Bingham plastic parameters.

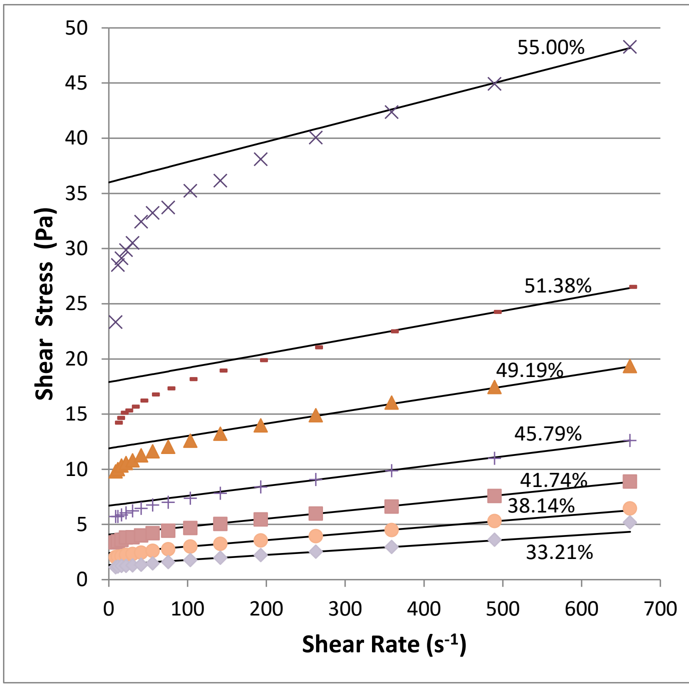

Figure 4 Rheograms

Figure 5 shows the Bingham parameters versus Cw approximated by exponential trend equations. The design rheology is summarised in Table 1.

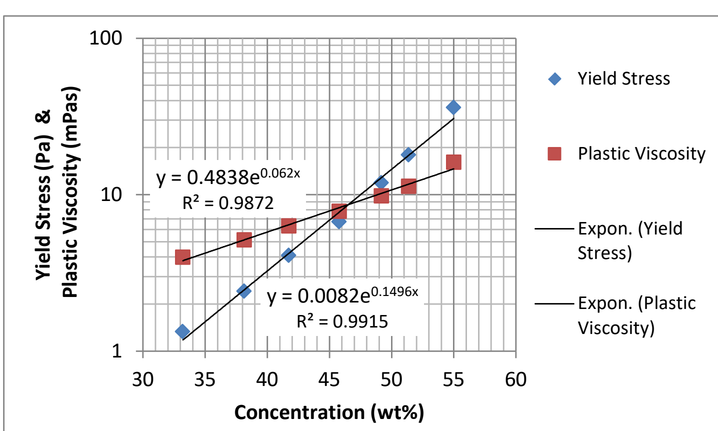

Figure 5 Yield Stress and Plastic Viscosity versus Concentration

Table 1 Design rheology

Concentration	38%	42%	45%
Yield Stress (Pa)	2.4	4.4	6.9
Plastic Viscosity (mPas)	5.1	6.5	7.9

2.6 Corrosion tests and predicted corrosion rate of steel pipeline

At the modest operating velocities (see Table 2), and based on the particle size distribution and rhe ology, pipe wear due to erosion was predicted to be relatively low. Most pipe wall thickness loss was expected to be due to corrosion.

The corrosion rate of steel pipe depends mainly on the Dissolved Oxygen Content (DOC) and the pH. Low DOC and high pH are likely to result in low corrosion rates. The tailings pH is high at around 10 so if the DOC is low then the corrosion rate can be expected to be low.

It was originally postulated that turbulent flow in the open channel may result in the tailings being fully oxygenated by the time the tailings reached the channel offtake point. However subsequent on-site measurements of DOC gave the following results:

- Slurry DOC measured at Concentrator, about 100 m downstream of existing thickeners, after hydraulic jump = 3.8 ppm at 14^0C
- Slurry DOC measured 3.5 kms along channel at proposed channel offtake = 3.4 ppm at 16^0C
- Saturated water calibration at channel offtake = 6.7 ppm at 14^0C

These results indicate:

a) The slurry DOC decreases during transport in the channel from the Concentrator to the offtake (from 3.8 ppm to 3.4 ppm), rather than increasing, as originally postulated. The 10% reduction is greater than the 4% reduction which would be expected purely from the 2^0C higher temperature at the offtake. This suggests that the slurry is consuming dissolved oxygen faster than oxygen is being absorbed due to the turbulent flow.
b) The slurry DOC at the channel offtake is about half that of fully saturated water

Corrosion tests were conducted in Slurry Systems' laboratory over a five hour period. At the start of the tests a nitrogen blanket was installed on top of the slurry. Once denied access to air, the agitated slurry slowly consumed dissolved oxygen The corrosion rate, as measured by a Corrater instrument, was monitored as the DOC reduced. Figure 6 shows a graph of measured corrosion rate versus DOC. The pH during these tests ranged from 9.7 to 9.0. The 3.4 ppm measured slurry DOC at the channel offtake suggests a corrosion rate of 0.22 mm/y. A design value of 0.25 mm/y was selected.

The mine had been in operation for 25 years and the unlined steel pipe flume from the Concentrator to the original thickeners has not been replaced and visually shows no sign of excessive wear at the exit into the thickener feed well. A corrosion rate of 0.25 mm/y equates to 6.25 mm metal loss over 25 years compared with the 25.4 mm wall thickness of the existing flume. The selected design value of 0.25 mm/y is therefore not inconsistent with observations on this flume.

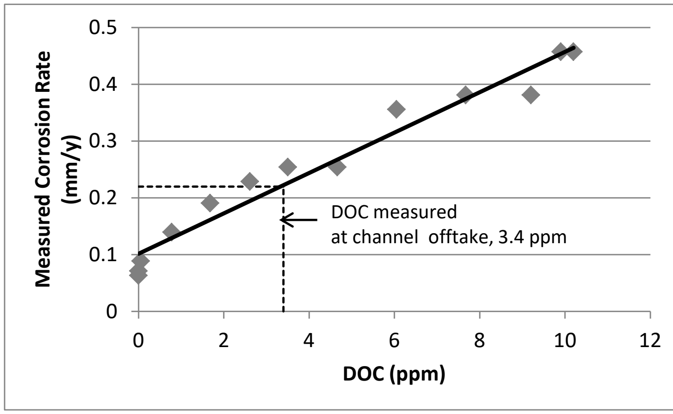

Figure 6 Measured corrosion rate versus DOC

The predicted wear rate of the rubber mine hose in the high velocity slack flow section at the start of the pipeline is discussed in Section 4.7.

3. DESCRIPTION OF SYSTEM

The 4,069 m long gravity pipeline system commences with a channel flow diversion system located approximately 3.5 kms from the Concentrator. The tailings are diverted from the channel into a drop box, then into a 1.5 m diameter concrete pipe under the roadway which discharges through a 10 mm safety screen into a screen chamber from which the gravity pipeline exits. The purpose of the safety screen is to prevent any plus 10 mm lumps which may have entered the channel from rock slides, entering the pipeline. A DN 80 pipe connection from the return water pipeline provides water for sprays which are directed onto the 10 mm screen. These sprays may be required to prevent a gradual build-up of dried slurry solids around the screen bars. The elevation of the pipe invert at the entrance to the pipeline is EL 2460 m and the elevation of the screens in the screen chamber is EL 2463.8.

Under normal operation, slack flow will exist in the first few hundred metres of the pipeline, and this section of the pipeline will be subject to high wear rates. Rubber mine hose is very resistant to wear and was selected for the first 310 m of the pipeline. (See Section 4.7). The hose is DN 1050, 16 mm liner thickness. The ID is 1042 mm to match the ID of the main steel pipeline. Flanges are ANSI Class 150.

Note: The alternative to a high velocity, slack flow pipeline in the 310 m initial slack flow section was to use a series of pressurised vertical drop boxes. This alternative was investigated but was discarded as being more expensive.

The initial portion of the rubber hose is laid at approximately 13% slope and consists of a 50 m straight section followed by a 21 m radius, 135 degree bend, leading to a 85 m straight section followed by another 135 degree bend of radius 55 m, then a 30 m straight section leading to the general pipeline route following the road alignment. For the remaining length of the slack flow section, the pipeline slope is approximately 11%. At the high slack flow velocities (see Section 4.7), lateral forces on the bends are considerable and significant anchoring is incorporated in the rubber hose section of the pipeline.

The remainder of the pipeline is of welded construction using unlined 12.7 mm wt DN 1050 API 5L X52 pipe, ID 1042 mm. ANSI Class 300 dump valves are installed at the low points at Chn 400 and Chn 3000.

The gravity pipeline discharges into a distribution box located at the top of the 20 m high paste thickeners. Discharge elevation is 27.8 m above ground level at the paste thickener site, i.e. pipeline discharge is at EL 2427.8 m. Flow from the distribution box to the 12 paste thickeners is by gravity with equal length discharge pipes from the underside of the box discharging into sloping open launders, to provide even distribution.

A DN 1050 return water pipeline (from the paste thickeners overflow water tank back to the concentrator) runs parallel with the slurry pipeline and upstream open channel system. This pipeline provides flush water to both the channel and pipeline when required.

4. HYDRAULICS

4.1 Maximum allowable operating head (MAOH)

Based on the 0.25 mm/y design corrosion rate, the wall thickness of the unlined steel pipe reduces from 12.7 mm in Year 1 to 5.2 mm in Year 30. Using a design factor of 0.72, the Maximum Allowable Operating Head (MAOH) for 45% concentration slurry is 444 m in Year 1 reducing to 182 m in Year 30. The MAOH for ANSI Class 300 flanges at the dump valves is 370 m at 45% concentration.

4.2 Head Loss Gradients

Table 2 summarises the predicted head loss gradients in the 1042 mm ID unlined steel pipe for pipe roughness values of 0.05 mm and 1.0 mm.

Table 2
Predicted head loss gradients
Steel pipe 1067 mm OD x 12.7 mm wt ID 1042 mm
Solids throughput 3,949 tph

Concentration	38%	42%	45%
Slurry SG	1.323	1.370	1.407
Flow Rate (m^3/h)	7,854	6,864	6,237
Velocity (m/s)	2.56	2.24	2.03
Head Loss Gradient (m/km), k=0.05 mm	3.81	2.72	2.25
Head Loss Gradient (m/km), k=1.0 mm	5.71	3.74	2.55

A design head loss gradient of 5.71 m/km at 38% concentration was selected. This allows for an increase in pipe roughness over time from 0.05 mm to 1 mm.

4.3 MAOH and hydraulic gradient lines

Figure 7 shows the design Cw=38% Hydraulic Gradient Line (HGL) and the operating HGLs for 45% and 38% concentrations. The horizontal dashed line is the maximum possible shutdown head, which can only occur if a pipeline blockage occurs.

Also shown in Figure 7 are the MAOH for 45% concentration slurry, for the 12.7 mm wall thickness steel pipe at Year 1 and for Year 30 based on 0.25 mm/y metal loss rate. There is sufficient margin between the maximum shutdown head and the Year 30 MAOH to allow for an average corrosion rate 30% higher than the design 0.25 mm/y.

The MAOH shown for the initial 310 m of rubber mine hose applies to the 700 kPa working pressure of the hose. Note that the hose burst pressure is 2800 kPa, four times the working pressure.

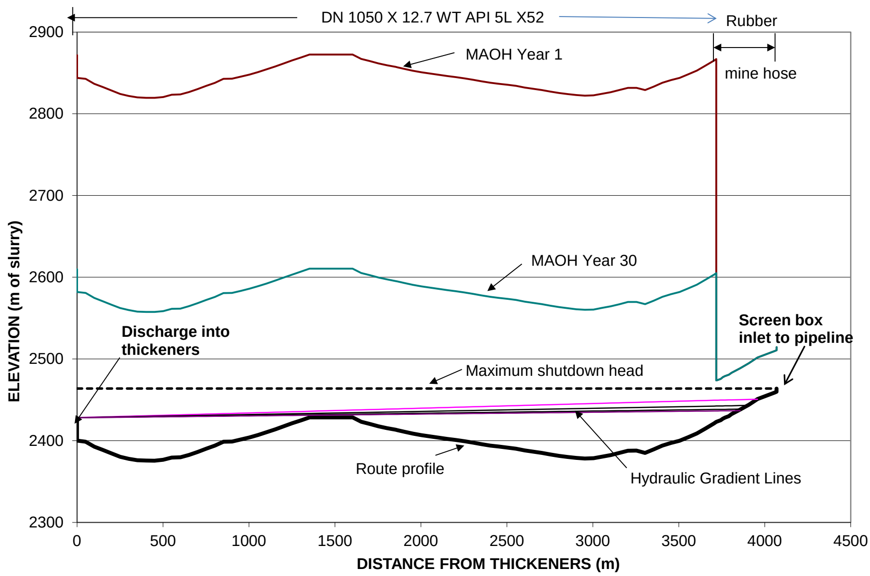

Figure 7 Hydraulic gradient lines and MAOH

4.4 Hydraulic Gradient Lines – Expanded Scale

Figure 8 shows the same Figure 7 Hydraulic Gradient Lines (HGL's) on an expanded vertical scale. The normal and maximum shutdown heads are also shown. The design HGL at Cw=38% is based on pipe roughness 1.0 mm. The other HGLs shown are based on a pipe roughness 0.05 mm. Figure 8 shows that there is a 13.2 m head margin from the screens in the screen box down to the design HGL. The margin is around to 25 m for normal operation.

In normal operation, tailings from the channel offtake are transported over the first 150 m to 250 m of pipeline in slack flow. In this section the slurry flows as in open channel flow with the slurry occupying only part of the pipe cross section and the velocity determined by the pipe slope. The velocity is predicted to be around 11 m/s. Pipe wear rates will be high but generally confined to the bottom of the pipe (see Section 4.7).

The flow regime changes from open channel to packed flow where the full pipe HGL's shown in Figure 8 intersect the route profile. The location of the transition between open channel and full pipe flow adjusts automatically to suit the required full pipe HGL.

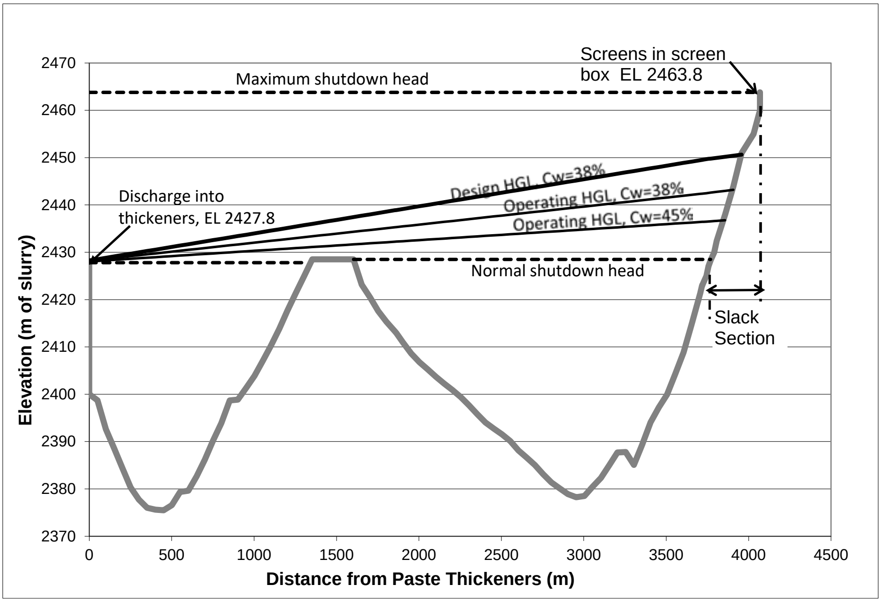

Figure 8 Hydraulic gradient lines with expanded vertical scale

4.5 Pipeline Shutdown

Long distance slurry pipelines are routinely shutdown for periods of 12 to 24 hours and restarted. In these pipelines, pipeline slopes are kept below 16% to prevent excessive concentration gradients occurring. Under shutdown conditions the slurry slowly settles vertically in the near horizontal pipe. As settling occurs, horizontal density currents are set up as higher density slurry at the bottom of the pipe cross section gravitates to pipeline valley locations, displacing lower density slurry at the top of the pipe cross section to pipeline high points. Experience has shown that a 16% slope limit prevents these concentration variations becoming excessive. All pipeline slopes in the Sar Cheshmeh gravity flow pipeline are within the 16% limit.

Since the Sar Cheshmeh gravity pipeline has slopes below 16% therefore in some respects the shutdown situation is similar to long distance pipelines. However there is a difference. When a long distance slurry pipeline is shut down, the discharge valve is closed to ensure packed conditions at all points in the pipeline. This prevents dribble flow from high points into valleys.

Dribble flow does occur during shutdown of the Sar Cheshmeh pipeline. The normal shutdown head shown in Figure 8 indicates that at Cw=38%, slurry will dribble down in the initial section of pipeline for about 120 m from Chn 3900 to Chn 3780, and for about 20 m from the high point at Chn 1350 to Chn 1330. During dribble flow, the velocity decreases as the shutdown HGL is approached. Low velocity flow can result in break-up of the slurry with coarser particles deposited. In some pipelines this may cause restart difficulties. However in the Sar Cheshmeh pipeline the dribble lengths involved are short relative to the total pipeline length and dribble flow was not expected to be a problem.

4.6 Pipeline Flushing

The recommended water flow rate during flushing is 5500 m^3/h. This provides a velocity of 1.79 m/s in the pipeline, sufficient to exceed the laminar/turbulent transition velocity at Cw=45%. At lower concentrations lower flushing rates can be used. For example the Operating Envelope (see later Figure 11) indicates a recommended minimum flow rate of 5000 m^3/h at Cw=42% and 4000 m^3/h at Cw=38%.

During flushing, the pipeline will normally continue to discharge slurry into the paste thickeners. An analysis was conducted to ensure there is sufficient head available when the head of the water batch reaches the bottom of a valley and is required to push the higher density slurry up the other side; the so-called U tube effect.

Consider Figure 9 which shows the situation at a flow rate of 5500 m^3/h when the head of the water batch reaches Chn 2950 at the bottom of the first valley. HGLs are based on a pipe roughness 1.0 mm. For a solids concentration of 45% the slurry HGL at Chn 2950 is at EL 2434.0 m. The ground elevation is 2378.2 m so the head of slurry required to maintain the flow is 2434.0 – 2378.2 = 55.8 m of slurry. With a slurry SG of 1.407 this head is equivalent to 78.5 m of water. Figure 9 shows this change in head at Chn 2950. The water HGL from Chn 2950 back to the pipeline inlet intersects the ground profile EL 2460 at the bottom of the screen chamber and at the inlet pipe invert. However the screen box screens are 3.8 m above the pipe invert so there is additional head margin available above requirements. At 38% concentration the water HGL intersects the ground profile at EL 2457, providing a 6.8 m head margin to the screens.

Figure 9 is based on head loss gradients for the design case rough pipe with a roughness of 1 mm. For new steel pipe roughness of 0.05 mm the HGLs at Cw=45% and Cw=38% are 5.8m and 10.8 m respectively below the screens when the head of the water batch is at Chn 2950.

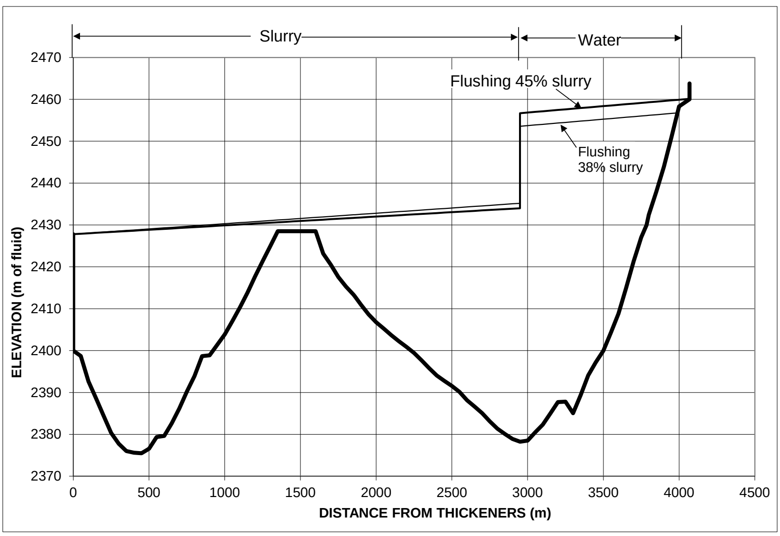

Figure 9 HGLs during flushing at 5500 m^3/h with head of water batch at Chn 2950, pipe roughness 1.0 mm

Another critical phase during flushing occurs when the head of the water batch reaches the bottom of the valley at Chn 450 m. Figure 10 shows the HGLs for this case when flushing at 5500 m^3/h. At Cw=45% the water HGL intersects 2.3 m below the screens in the screen box. At Cw=38% the water HGL intersects the route profile 6.8 m below the screens.

Figure 10 is based on head loss gradients for the design case rough pipe with a roughness of 1 mm. For new steel pipe roughness of 0.05 mm the HGLs at Cw=45% and Cw=38% are 6.8 m and 10.8 m respectively below the screens when the head of the water batch is at Chn 450.

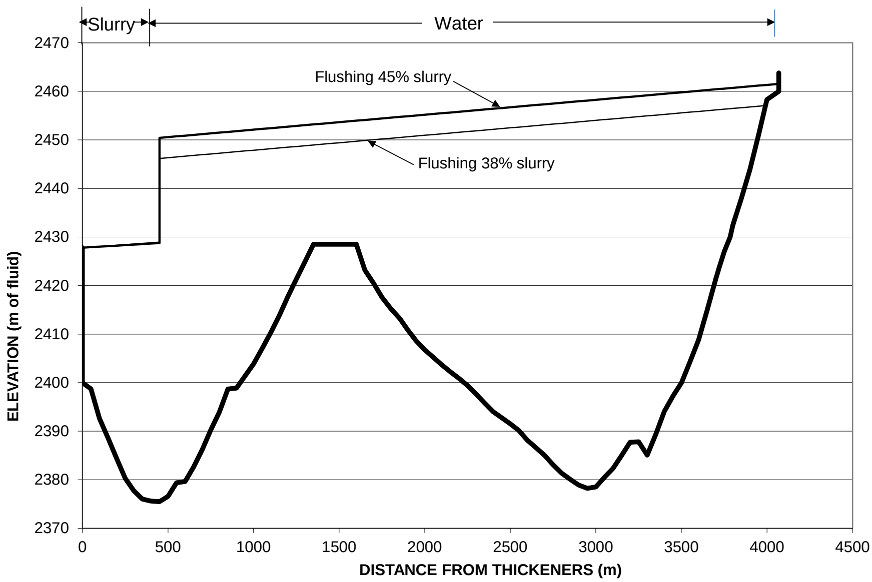

Figure 10 HGLs during flushing at 5500 m^3/h with head of water batch at Chn 450, pipe roughness 1.0 mm

Figures 9 and 10 indicate the minimum head margins during flushing. When the head of the water batch is not at the low points at Chn 2950 and Chn 450, the water HGL's will be lower and the head margins increase.

4.7 Rubber Mine Hose, Slack Flow Section

Figure 8 shows the full pipe HGLs intersecting the route profile between Chn 3860 (EL 2437) and Chn 3900 (EL 2443). For Chns greater than the full pipe/slack flow intersection point, slack flow exists. In slack flow the slurry flows in open channel flow with the slurry occupying only part of the pipe cross section and the velocity determined by the pipe slope. The velocity is predicted to be approximately 11 m/s. Pipe wear rates will be very high but generally confined to the bottom third of the pipe. The initial 310 m of pipeline includes two bends. There is likely to be additional wear in these bends compared with the straight pipe sections.

The flow regime changes from open channel to packed flow where the full pipe HGL's shown in Figure 8 intersect the route profile. There is very high turbulence in this transition zone and very high pipe wear rates may occur with wear not only confined to the bottom of the pipe. However this transition zone will move back and forth along the pipeline as the flow rate and concentration varies, so the higher wear should be distributed along the pipeline.

If the pipeline is shutdown with slurry in the line, the slurry/air interface will eventually be stationary at Chn 3769 (EL 2428.5), as seen in Figure 8. When slurry enters the pipeline during restart, the high turbulence transition zone between slack flow and full pipe flow will initially be at Chn 3769. Hence wear resistant pipe is required at least down to this point. For design purposes rubber mine hose was installed down to EL 2416 (Chn 3668). The total length of rubber mine hose installed is 310 m.

It is difficult to accurately predict pipe wear rates in this slack flow region. Our best estimate is that 25 mm thickness of rubber lining is required for the 30 year life. The rubber mine hose has a wall thickness of 16 mm suggesting that the required 30 year life could be met by rotating the rubber hose.

5. OPERATING ENVELOPE

Figure 11 shows the predicted Operating Envelope of the gravity flow pipeline with the 38%, 42% and 45% concentration design points (Table 2) indicated. It is obvious that the pipeline is capable of transporting a considerable range of throughputs and concentrations.

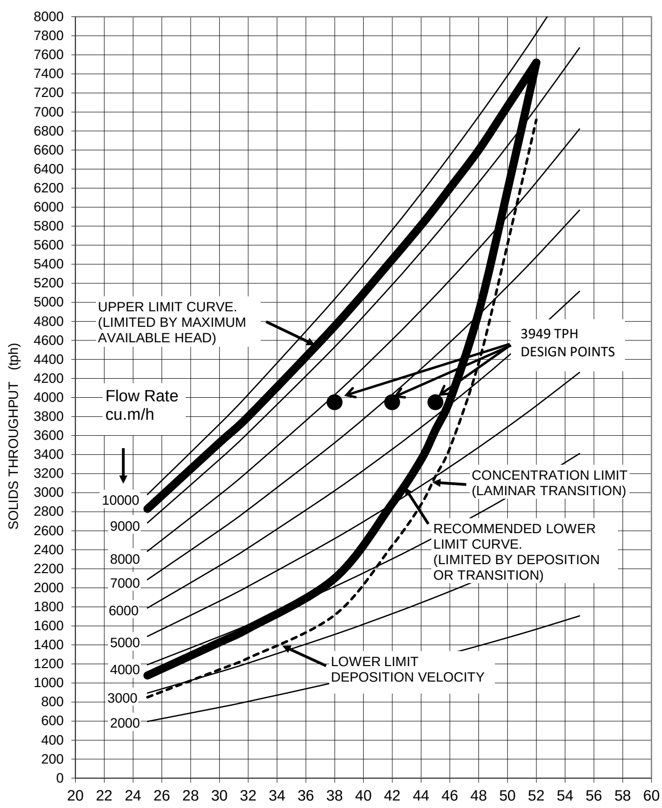

Figure 11 Operating envelope

6. OPERATING EXPERIENCE

6.1 Throughput

The gravity flow pipeline has been transporting tailings since mid-2012 when the paste thickeners became operational. In the four year period from July 2012 to July 2016, a total of 94,529,523 tonnes was transported through the pipeline. This represents an average of 23.6 Mtpa or 2698 t/h.

Over the first 201 days of 2016 a total of 15,411,863 tonnes was transported representing an average daily rate of 76,676 tonnes, or an average 3,195 t/h, equivalent to an average 28 Mtpa. During this period, the concentration ranging between 30% and 47%.

The highest daily rate transported has been 95,504 tonnes, equivalent to 34.9 Mtpa or 3979 t/h average. The concentration was 42% indicating a flow rate of 6915 m^3/h. Considering the Operating Envelope (Figure 11), this highest daily rate is almost exactly equal to the 3949 t/h, Cw=42% design point. As can be seen from the Operating Envelope, the pipeline is capable of transporting considerably higher solids throughputs than this highest observed daily rate. Currently the maximum throughput is limited by Concentrator production rather than the pipeline.

6.2 Pipe Wear

In October 2013 pipeline wall thickness measurements were conducted. Measurements were taken at right side of the pipe, bottom, left side and top, at 179 different locations along the pipeline. The average wall thickness readings were:

Right side, 12.74 mm
Bottom, 12.65 mm
Left side, 12.73 mm
Top, 12.69 mm

The nominal new pipe wall thickness is 12.7 mm so very little wall thickness loss is indicated, perhaps about 0.1 mm at the bottom of the pipe over about a 15 month period. The annual wall thickness loss is therefore well within the 0.25 mm/y design corrosion rate.

During further wall thickness measurements conducted in November 2015, scale formation was detected.

7. ACKNOWLEDGEMENTS

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