ON-LINE MEASUREMENTS OF
CRITICAL DEPOSITION VELOCITIES
FOR FLOW OPTIMISATION

H J Ilgner, CSIR
ABSTRACT

The paper summarises recent results for instrumented critical deposition velocity measurements and provides a novel approach to applying slurry and paste flow control in order to reduce water and energy consumption.

The results from on-line instrumentation to detect critical flow conditions at the pipe invert are compared with visual observations, which are traditionally carried out during full-scale slurry test work. The limitations and possibilities of some commercially available instruments are reviewed.

Concepts of a novel method to reduce purposely the mean velocity within a limited section of the pipeline to enable the controlled development of a sliding or stationary bed are discussed. This method would enable the use of the ultrasonic Transflection © technique, but would require significant instrumentation to detect any gradual settlement, which may occur only after a few kilometres inside the pipeline.

Small, self-heating thermal sensors, which are able to quantify the amount of heat removal which is proportional to slurry/paste movement along their front face, have been incorporated into an overall flow control philosophy. The thermal sensors can be mounted flush with the inner pipe wall at the invert position of a horizontal pipe. From that position, it is possible to obtain a 4 to 20 mA signal, which is proportionate to the flow conditions at the invert of the pipe. The signal indicates the transition from a high-velocity, fully turbulent flow condition to the onset of sliding bed behaviour but, most important, it indicates clearly the condition of a stationary bed with no heat removal.

This control philosophy can be retrofitted to existing tailings and even paste pipelines to control and optimise the flow conditions, thereby saving energy, water and operating costs.

1 INTRODUCTION

The combined tailings from platinum and gold-producing plants currently amount to about 150 million tons annually (DME, 2003). The tailings-disposal dams are generally situated a few kilometres away from the metallurgical plants. The tailings are pumped by means of multi-stage centrifugal pumps at reasonable slurry concentrations by volume of between 25 and 35 %. Only in the diamond industry is paste disposal of thickened tailings practised due to an acute shortage of water in those mining areas (Dunn and Vietti, 2003).

It has been estimated that a total of almost 200 million kWh is consumed annually in the pumping of gold and platinum tailings to the surface disposal dams. This excludes the power consumed in pumping excess water from the dam back to the plant. Therefore, scope exists in this field to meaningfully impact on national energy savings.

To address the national energy-savings imperative, the CSIR is investigating the potential benefits of pumping tailings at a higher concentration and at a lower transport velocity than currently practised. This can reduce the energy consumption per ton per km and the volume of water pumped to the dams, as well as the amount of water...
returned from the dams to the plant. Higher-density placement onto the slimes dams will reduce the pond area on top of the dam and will therefore reduce water losses due to evaporation.

2 NEED TO REDUCE ENERGY AND WATER CONSUMPTION

Over the next few years, energy and water costs are expected to rise significantly. There are various incentive schemes for reducing energy and water usage. Compliance with the legal limits will be enforced and audited. Penalties may be issued for non-compliance.

An innovative method of controlling and optimising slurry flow to minimise water and energy consumption is presented in this paper. This method could be a vital component in increasing the reliability of slurry and paste operations, as well as in reducing operating costs. Holistic decision-making will be applied to select the most appropriate operating point, based on site-specific preferences and in situ slurry and paste properties.

3 CURRENT PRACTICE AND POTENTIAL BENEFITS

3.1 Current tailings pumping practice

Full-scale pressure loss data are generally available to provide a basis for pipeline system design. An important pipeline design consideration is the critical deposition velocity at which particles begin to become stationary at the invert of the pipe. Critical deposition velocities are best determined by observation through transparent pipe viewing sections. This slurry-specific information can then be up-scaled theoretically with some degree of confidence. The major factors affecting the critical deposition velocity are slurry concentration, pipe internal diameter, particle size distribution and particle specific density.

Particularly in the platinum industry, it is normal practice to mix tailings from the Merensky reef (typical solids specific gravity of 3.1) with those from the UG2 reef (typical solids specific gravity of up to 3.9) for co-disposal through one pipeline. The mix ratios depend on the grade and tonnage from the various mining areas and are determined by the optimisation of the metallurgical extraction, rather than by consideration of the optimal economic pumping parameters for tailings disposal.

To ensure stable pipeline operations, even if the duty point varies, or to accommodate a known operating envelope, it is still common and good practice to design and operate the overland pipelines with a considerable safety margin. This safety margin is, however, more a factor to guard against uncertainty, to cover all possible adverse operating conditions during the life of the pipeline, including likely variations in the tailings composition. However, this over-design comes with higher operating costs due to pumping being done at higher velocities and at a lower concentration than is technically possible.

If on-line instrumentation could continuously monitor the slurry flow behaviour at the pipe invert, this could enable the slurry/paste concentration and velocity to be...
optimised. At the same time, the pipeline could operate safely at reduced velocities and increased concentration, thus ensuring that the same tonnage is pumped, but with less energy and water consumption.

As part of mine dump reclamation and site rehabilitation initiatives, tailings are also being pumped from dams to process plants to recover residual value. These pumping systems are mostly temporarily installed and are often not optimised, either consuming excess power or operating below the safety margin, and thus have been shown potentially to suffer from unsatisfactory performances.

The natural variability of the properties of reclaimed tailings (coarse particles at the dam circumferences, and ultrafines in the dam centre) requires either a pump system design with a large safety margin for excess velocity (and thus excess energy consumption) to prevent settlement under all slurry conditions, or on-line instrumentation that would be able to measure the critical deposition velocity in situ in the pipe invert.

Operating problems are also experienced in conventional tailings pipelines, when the available pipe types and pipeline lengths are not correctly matched to the actual pump-duty points (Davel and Robinson, 2003). A recent example of poor design and insufficient supervision was the 1994 failure of the Merriespruit No. 4a dam, when 17 people were killed. The technical background and root causes were described in detail by Davel and Robinson (2003). The dam was not supposed to have been in use since 1993, but the design of the tailings pipeline to the new dam was inadequate to deal with certain process conditions, i.e. dilute tailings due to excess water addition. Low-density tailings were therefore at times again discharged unduly into No. 4a dam, eventually blocking the penstock. This was not detected due to inadequacies in the management aspects of the stewardship of the tailings dam (Martin et al., 2002), which gradually led to the filling up of the dam. Eventually, the dam over-topped ‘due to rain’ and the wall failed catastrophically.

3.2 Most economical operating point

It is well established that the most economical operating condition for slurries is just above the critical deposition velocity. This velocity is often determined in transparent viewing sections during test work conducted with a sample that is as representative as possible of the expected typical slurry composition or the worst-case composition expected during the life of the pipeline.

In reality, however, the slurry ultrafines content in the particle size distribution, the maximum particle size and the mineral composition may vary considerably. Especially if the slurry contains larger particles, they will tend to settle out first and this may lead to undesired, unstable operating conditions. A detailed analysis of the potential problems associated with settlement due to laminar flow conditions was presented by Cooke (2002). It was demonstrated that for larger pipe diameters, i.e. when pipeline pressure losses are below 1 to 2 kPa/m, there is no resuspension mechanism in place and the pipeline may eventually become blocked.
Increasingly, most plants are now controlled by sophisticated PLCs. As most commercial flow meters for slurries and pastes measure over the pipe's entire cross-sectional area, they cannot detect the onset of the sliding and stationary bed flow modes.

### 3.2 Envisaged pumping system with flow optimisation

An optimised tailings disposal system has to provide operational stability, while minimising power consumption and pipe wear. For settling slurries, the velocity at which the pressure loss and thus the power consumption are at a minimum, thus representing the most economical conditions (Baker et al., 1979), is often, but not always, associated with the critical deposition velocity (Thomas, 1979).

System stability is generally the major design driver, rather than the minimum deposition velocity. Stability is determined by the appropriate matching of pump head characteristics with pipeline characteristics. By ensuring that the interception of both characteristics provides a stable operating point, the mean velocity in the pipeline can be maintained at close to the critical deposition velocity. There is then no need to design and pump at high velocities, which wastes energy and creates unnecessary pipe wear.

### 4 BRIEF LITERATURE REVIEW

Most of the available literature shows that in the past, various measuring techniques were used with rather low-density slurries, or slurries with relatively coarse sand particles. The results were vital to furthering the understanding of slurry behaviour and to developing predictive models. Particularly useful is the two-layer model (Wilson et al., 1992), which considers bed load and can be used in the system design for determining critical deposition limits.

Some techniques for measuring critical deposition velocities during slurry tests are video (Simkhis et al., 1999), photo-electric, electro-resistive and even neural networks as early as in 1993 (Wiedenroth), as well as some custom-made prototype temperature sensors with self-heating properties on a test facility in Italy (Ercolani et al., 1979). A subsequent, independent evaluation of those thermal probes in Canada, however, yielded unsatisfactory performance at the time. An ultrasonic ‘bed-load velocimeter’ with sophisticated processing correlations was also developed and tested temporarily in a pipe with a large diameter for different slurry types (Lazarus and Lazarus, 1988). Unfortunately, most of these instruments are used only in R&D environments with skilled operators, and are not commercially available for industrial use.

A brief review of special methods for measuring the critical deposition velocity during slurry pumping was published recently (Ilgner, 2004). It was again apparent that these were applied mostly in research laboratories under skilful supervision, but not widely in industrial applications. The only exception was the complex Transfection© method, in which ultrasonic patterns are successively beamed into the slurry flow to track particle motion. The basic principle of this technique is shown in Figure 1.
Figure 1. Principle of particle tracking, using the ultrasonic Transflection® principle (from Panametrics' brochure).

The DF 868 flowmeter applies an ultrasonic Transflection® technique (developed and patented by Panametrics) and is particularly suitable for high-density slurries, in which conventional transit-time flow meters fail. Coded transmissions and cross-correlation detection are used to analyse ultrasonic bursts, which are repeatedly sent into the slurry at an angle from sensors clamped onto the pipeline. Two sensors are used in parallel, which alternate as receiver and emitter. The positions of the two sensors relative to each other and their target area are shown in Figure 1 above.

Since this technique measures in situ velocities at a certain level within the pipe, it is implied that when no velocity is measured whilst flow continues, stationary deposition conditions apply at that level. The instrument also quantifies the quality of the received and processed velocity signal by assigning a numerical value to it. This value is termed the incoherence of the signal and is provided as an output of between 4 and 20 mA.

A major disadvantage of this instrument is that the measurement is taken not directly at the pipe wall, where it would be of interest, but at a point significantly above the pipe invert within the moving slurry. This point has to be at a distance of at least 10% of the pipe's internal diameter, e.g. at 15 mm above the pipe invert for an internal pipe diameter of 150 mm. Thus, stationary bed conditions may be observed at the invert, while the slurry is still moving slowly at the target zone, located at 15% of the internal diameter above the invert.

5 TEST WORK WITH THE TRANSFLECTION TECHNIQUE

5.1 Instrumentation set-up

For measurements of sliding bed behaviour or stationary bed conditions, the two sensors shown on the side of the pipe in Figure 1 above must be located at the bottom of the pipe. Such an installation of the sensors on a 150 mm viewing section is shown in Figure 2 below.
Figure 2. Transflection sensors mounted on an NB 150 pipe loop, filled with water

The analytical data-processing software is supplied with the Panametrics DF 868 and was especially adjusted on site by the agent within its available, standard options provided by the manufacturer. The settings were fine-tuned to allow for very low velocity measurements (about 0.5 m/s) before the output of the velocity signal dropped to zero. As soon as the incoherence rises above an internal threshold, the output drops to zero at a certain mean velocity. Unfortunately, it was found that it takes a considerable time before the instrument commences to provide data again, and an increase in velocity is required to obtain a further good signal with an acceptable incoherence. It must be remembered that the instrument is mostly used as a genuine flow meter, and the settings for point-tracking within a local, limited area in a pipe represent an exceptional application. Nevertheless, the available software options proved to be sufficient for the intended purpose.

Figure 3 shows typical behaviour of an increased incoherence as the mean velocity decreased. The incoherence signal was very stable at about 500 for high velocities of about 3.5 m/s when fully turbulent conditions prevailed.

Figure 3. Gradual increase in incoherence due to decreasing velocity

It can be seen that with the development of a stationary bed at the invert of the pipe, at a mean velocity of 1.5 m/s, the fluctuations of the incoherence increase due to increasingly unstable conditions.
The results presented in Figures 4 and 5 were obtained in an NB 150 pipe loop by recording the slurry flow rate and the measured incoherence for different slurry concentrations and velocities. An increase in the incoherence was measured while the velocity was being gradually reduced.

5.2 Tailings tested

Two distinctly different slurry types were selected for comparing the performance of the equipment for measuring critical deposition in situ. A typical platinum tailings sample with a high fines content was used for the test programme, as well as a gold tailings sample. The latter slurry was deslimed to provide a fast-settling slurry type. More details of the slurry types were published previously (Ilgner, 2004). Since testing in small internal diameter pipes, i.e. below 100 mm, may prevent deposition in the turbulent flow regime due to the high pipeline pressure losses (Cooke, 2002), an NB 150 closed loop with a glandless centrifugal pump was used for the test work. The water and solids contents were varied, and slurry samples were taken to enable the delivered solids concentrations to be determined accurately in the laboratory.

5.3 Results and discussion

Deslimed gold plant tailings were used to evaluate the performance of the Transflection technique. The scatter of data for the incoherence is shown in Figure 4 below for four different slurry relative densities (RD) and solids concentrations (Cv).

![Figure 4. Scatter and trends of incoherence for deslimed gold tailings slurries](image-url)
The charts show that the observed critical velocity increases with increasing slurry concentration, and that the same trend was evident for the lowest mean velocity at which incoherence was still measurable. A summary of all the test points, observation data and operating conditions is shown later in Figure 6.

Each chart above comprises a data set, which includes three runs in which the flow rates were gradually reduced repeatedly. A large scatter is evident for low slurry velocities. Although the instrument was set at a point that was at 12% of the vertical height of the internal pipe diameter, the readings may also have been affected by particle movement (or non-movement) in the area surrounding that point. The lowest mean velocity at which it was still possible to measure was significantly lower than the observed critical deposition velocity, due to the reading being at 12% above the invert.

As an alternative slurry type to the deslimed gold plant tailings, platinum tailings with a higher fines content were also used to evaluate the performance of the Transflection measuring technique. The data points for the measured incoherence for different slurry concentrations over a range of mean velocities and different concentrations are shown in the charts in Figure 5 below.
The data points for each slurry concentration are summarised by a trend line to enable comparisons to be made. For this type of slurry, it was evident that with increasing slurry concentrations, the incoherence increased at a lower mean velocity prior to dropping to zero output due to unacceptable incoherence. The chart at the bottom right of Figure 5 above shows a comparison of the trend lines for each concentration. The general trend is in line with the observed lower critical deposition velocities. The instrument continues to provide incoherence values at mean velocities far below critical deposition, but it does not identify the actual onset of a stationary bed due to the angle at which it measures in the pipeline. However, by employing the proposed two-diameter concept outlined in Figure 7, it may be possible to use the instrument to measure and optimise flow conditions. The results from the Transflection instrument indicate that the critical deposition velocity for platinum tailings decreases with increasing slurry concentration by volume within the range tested of up to 30 %. The opposite effect was indicated with the deslimed gold tailings for solids concentrations by volume of upwards of 28 %, as shown in Figure 6 below.

**Figure 6. Observed and lowest measured velocities**

Good correlation between the slurry-specific dependency of the observed critical deposition velocity and the lowest measured velocity is evident. Unfortunately, owing to time constraints, the test programme was not able to accommodate the same ranges of slurry concentrations for both slurry types. Similar gradients, with a clear local minimum for the deposition velocity at a solids concentration by volume of about 30 %, were published elsewhere previously for different slurry types (Thomas, 1979).

For the instrument to be integrated into a control philosophy, additional data processing would be required to take the scatter into account. However, the average increase of incoherence, as well as the point velocity, which is also provided as an output of the instrument, are convenient indicators, in a user-friendly 4-20 mA format, of the slurry behaviour above the pipe invert. Thus, it should be possible to measure sliding bed behaviour with this instrument, particularly for slurry containing larger particles, which settle out much faster that the remaining smaller ones.
6 REQUIREMENTS FOR IN SITU INSTRUMENTATION

Although a large number of probes and techniques for the measurement and detection of critical deposition velocities have been installed at various test centres, it appears that most of the instruments are rather complex and the interpretation of their output requires dedicated, knowledgeable staff. For this reason, in a comprehensive slurry technology paper (Heywood, 1999), no reference was made to any of these probes for the in-line measurement of critical deposition velocities for the purpose of controlling slurry systems. This reflects the current practice of using various predictive models, applying experience and good judgement to select the most applicable model, and then adding at least 25% to the design velocity to obtain a safety margin.

This practice, coupled with the unfortunate reality that many slurry systems do not always receive sufficient maintenance attention, leads one to the conclusion that slurry control instrumentation for industrial usage would have to be robust, reliable and simple to maintain and analyse. The higher the level of complexity of the instrumentation, the higher the skills required of the maintenance staff, otherwise it will not remain a vital part of the system control. Techniques that require complex calibration or special analytical algorithms therefore do not appear to be suitable for industrial applications.

6.1 Zone of influence

Acoustic and electro-resistivity probes sense over a large volume in the pipe, and the ratio of signal to noise is critical. Although the ultrasonic Doppler methods zoom in on a specific point or area, the signal is affected by boundary conditions. The most direct and area-focused technique for determining critical deposition velocities or sliding bed conditions is the optical technique as only the condition immediately at the pipe wall is recognised. However, abrasive wear on the inner pipe surface impedes any long-term industrial use of this method.

6.2 Response time

The response time varies between the various sensor types due to the necessity for data processing or due to sensor inertia. Fast response times—within a second—are desirable to detect the erratic sliding bed behaviour associated with the onset of a stationary bed. However, in such situations the sensor signal becomes increasingly noisy and difficult to use for control.

The Transflection instrument is able to “observe” the slurry behaviour for up to 10 seconds without changing the output signal. Only once the received and processed signals provide sufficient repeatability to be fully representative of that particular period of time, is the output value updated.

6.3 Minimising the zone of influence

Although non-invasive probes, such as are used in ultrasonic techniques and some electro-resistive methods, measure a larger area, the thermal probes are mounted flush with the internal pipe wall. The temperature of the probe itself is therefore measured and good thermal conductivity to the moving or stationary slurry will provide a quick
response signal. The output of the probe is affected only by the slurry or paste that is in
direct contact with it, thus eliminating any electrical, inductive, acoustic or chemical
effects. This measuring technique is most promising and is being further pursued
because of its sharp zone of influence, quick response time, robustness and simplicity.

6.4 Use of a larger-diameter pipe section to induce settlement

To avoid the risk of having the entire length of a pipeline (of a few kilometres)
operating near the critical deposition velocity, it is proposed that a limited section of the
pipeline (say a length of about 50 m) be replaced with a pipe of a slightly larger internal
diameter. The purpose of this pipe section is to maintain a stationary control bed at all
times, while the main length of pipeline operates without any stationary bed, but near
the economic optimum. The control instrumentation is installed at the section with the
larger pipe diameter. If no stationary bed is detected in the larger-diameter section, then
the remainder of the pipeline is being operated at unnecessarily high velocities above
the economic optimum.

Correspondingly, if the height of the stationary bed in the shorter length, larger-diameter
section increases above a certain level, sliding bed conditions will arise along the longer
length, smaller-diameter pipeline. Thus, it is important to install instrumentation that is
able to detect not only stationary bed conditions, but preferably also the extent (either
height or width) of the stationary bed.

In contrast to the conventional way of trying to prevent the onset of stationary bed
conditions, this two-diameter method encourages the ongoing in situ presence of a
stationary bed in order to detect it for whatever slurry composition is being pumped.
The limited height condition of the bed is then used to control the mean velocity in the
smaller-diameter pipeline while increasing the solids concentration to achieve the most
favourable economic operating conditions. Figure 7 shows the principle of the two-
diameter control method, and the proposed position of various probes.

![Thermal side sensor](image)

![Thermal bottom sensor](image)

![Transflection sensors](image)

Limited length with larger internal diameter to induce stationary control bed

Figure 7. Section with larger internal diameter used to induce stationary control
bed conditions
6.5 Maximising the control signal

Assuming a section with a larger internal diameter as part of the control philosophy, and by employing a sensor with a sharp zone of influence, the following option for operating the entire pipeline at various set points is envisaged. A bottom reference sensor is located at the invert of the pipe, with a side sensor mounted radially at the circumference of the pipe. While stationary conditions prevail at the pipe invert, thus covering only the bottom sensor, the difference in signals between the bottom and side sensors is maximised. This concept is shown in Figure 8 below.

![Maximum signal output to enable flow control](image)

**Figure 8: Maximising signal amplitude with induced stationary control bed**

7 APPLICATION OF THERMAL PROBES

Temperature probes with a self-heating property have been used in the past to measure the onset of unsteady bed conditions on one test site (Ercolani et al., 1979), but have not been used elsewhere. One probe was located in the upper pipe section and penetrated into the slurry stream to measure the mean slurry temperature. A second probe was mounted flush at the pipe invert. The temperature signals were compared and the differences were used to detect various bed conditions. As soon as a stationary bed developed, even for a short period of time, the slurry did not remove any heat build-up from the bottom probe, thus creating a measurable temperature differential between the separate probes. However, this type of custom-made probe was not further developed or implemented. The sensors used in this operation were very basic.

7.1 Principle of probe operation and installation

With significant advances in sensor development after the initial use of a thermal probe in Italy in 1979, mature thermal flow probes are now available with stabilised output signals. The manufacturers recommend their use for overall flow measurements, where they have to protrude into the flow stream in order to measure a signal proportional to
the flow rate. For that purpose, the manufacturers also advise not to install them at the pipe invert, and not flush with the inner pipe wall. The following description is therefore an unconventional application.

For critical deposition velocity measurement, the thermal sensors are mounted flush with the internal pipe wall. The basic principle of the thermal sensors is shown in Figure 9. The basis is an equilibrium between the heat supply to the sensor face and the small heat absorption by the moving, or non-moving, slurry paste passing the sensor face. Each sensor has two internal temperature probes and a central heating element. Irrespective of the individual paste and the ambient temperatures, the sensor's own control circuit maintains a certain temperature differential between the two temperature probes during paste flow. As the paste velocity changes, so does the heat-removal rate and, correspondingly, the heat input required to maintain the constant temperature difference.

\[\text{Paste flow direction} \quad \text{Heat exchange along sensor face} \quad \text{Transferred heat} \sim \text{paste velocity} \]

\[\text{Pipe wall} \quad \text{Heat input} \sim \text{paste velocity} \quad \text{Weld-on stub} \]

\[\text{Temperature 'before'} \quad \text{Temperature 'after paste passing'} \]

**Figure 9. Principle of heat exchange between thermal sensor and flow medium**

The sensor output needs to be calibrated with the observed velocity at the pipe invert for individual slurry and paste types. Thereafter, the analogue sensor output (4 to 20 mA) is scaled directly into the velocity at the pipe invert. Thus, fully turbulent flow conditions, sliding bed behaviour and even stationary bed conditions are detected and can be used for flow control.

The most significant information given by the sensor, however, pertains to the condition of either flow or the indication of 'no heat removal'. The latter signifies a stationary bed condition, and, when detected on-line as part of a monitoring and control strategy, this indication can be used to initiate corrective actions to prevent pipeline blockages.

### 7.2 Laboratory test rig set-up

A small test loop was set up to study the performance of different thermal sensor types and to obtain operating reference points prior to large-scale testing. Figure 10 shows the test rig and various sensor types mounted on a transparent pipe section.
The photo on the left shows the large drum with flush water, the mixing tank and the Mono pump below, driven by a variable speed DC motor. The photo on the right shows two sets of three thermal sensors each mounted at various positions around the pipe circumferences. Two further sensors tested employ different measuring techniques, one of them using two metal contact points to apply a magnetic-inductive technique to determine flow or no-flow conditions.

The photo on the left in Figure 11 below shows the flush-mounted front end of a thermal sensor in the transparent viewing section. The photo on the right shows a stationary bed layer, covering approximated 25% of the pipe diameter.

An asymmetrical velocity distribution profile may develop under certain flow conditions. The extent of the unevenness can be quantified with the sensors, if they are placed at selected positions around the pipe.

Figure 12 shows the rationale employed in positioning of the sensors for detecting such differences in slurry wall velocities for the bottom, side and top sensors location, as shown in Figure 10, for different conditions in the pipe.
Similar velocities at all three thermal sensors:

Stationary bed covers

Bottom sensor:

Stationary bed covers

Side sensor too:

Figure 12. Location of thermal sensors around pipe circumference and velocity indications

The slurry velocity range of interest is from 0 m/s to about 0.5 m/s to detect sliding and stationary bed conditions. In vertical pipe orientation, or in horizontal orientation under fast flow conditions, all three sensors show similar outputs, indicating flow over the entire cross-sectional area of the pipe. As soon as a sliding bed, or when a limited stationary bed develops, the sensors on the bottom will provide a reduced output. This output is independent of local increases in density, particle size, etc. It is governed mainly the reduced heat removal due to localised decreases in velocity. The sensors have a very limited zone of influence, ‘seeing’ only the motion of the slurry/paste directly along the sensor face that is exposed to the slurry/paste. The difference between the upper sensor and that at the pipe invert indicates any uneven velocity distribution in the pipe, which is of interest in quantifying slurry and paste flow patterns.

7.3 Typical response for settling slurries

For settling slurries, the sensor configuration has to have a fast response time to detect moving beds and stationary beds as they develop. If the bottom sensor indicates no movement, but the side-mounted sensor next to it indicates flow, then the extent of the stationary bed is limited and is still between the two sensor positions, as shown in the middle in Figure 12. This condition occurred at 17:23, Point ‘A’ in Figure 13.
Figure 13 shows that the flow rate through the horizontal test section was reduced in distinct steps. The responses of the two sensors as a result of the reduction in flow rate and the reduction in velocity at the bottom and side sensors are shown clearly. The sensors have a rapid response time and are sufficiently stable for constant flow conditions.

At 17:35, the flow rate was increased again in steps. As expected, the side sensor responded first, doing so at 17:36 when the stationary bed was observed to be removed in an instant. The same direct response was evidenced for the bottom sensor when the mean velocity (flow) was further increased in steps. At 17:45, the bottom sensor responded after the stationary bed had been removed completely due to the increased mean velocity.

The most important feature, however, is that the sensors provide a 4-20 mA output signal, which can be utilised for slurry flow control, based on actual in situ measurements. The sensors are therefore able to detect the effect on the wall velocity due to whatever variation in the slurry/paste composition may occur for the following parameters:

- Overall flow rate through the pipeline
- Slurry concentration by mass or volume
- Particle top size
- Particle size distribution
- Specific gravity of the solids fractions
- Mineralogy
- Surface effects between solids and liquid.

8 CONTROL PHILOSOPHY FOR FLOW OPTIMISATION

There are increasing incentives to reduce the water content of tailings being pumped to the slimes dams, for both typical tailings and high-density, thickened tailings (Jewell et al., 2002). Especially for conventional tailings, supplementary water quantities may need to be added to achieve a desired design flow rate to provide the safety margin for avoiding settlement along the pipeline.

Generally, it is good practice for pump system designs to take variations of tonnage and slurry density into account to prevent potential settlement by increasing the velocity by a factor above the minimum required velocity. Even if large-scale pumping test work were conducted initially, prior to the design of the pipeline, the system design would be based mainly on the properties of the one sample used for the test work.

Some pipelines may have dual-duty purposes: they transport either a fine slurry, or a mixture of fines and coarse particles at an other operating point. Each slurry would have its own make-up recipe and operating point. However, fluctuations due to process variations do occur. In order to ensure stable operating points at all times (Wilson et al., 1992), transport velocities often have to be designed consciously above the critical deposition velocity to accommodate any unforeseen effects of variable slurry compositions.
During the life of the pump station, slurry conditions may vary substantially, particularly with ongoing metallurgical process optimisations. Some plants will increase their tonnage, and/or the fineness of the milled tailings will increase. Some disposal pump systems, such as in the platinum industry where Merensky and UG2-based tailings are combined at variable ratios for deposition, will experience different mineralogies and solids specific gravities. These parameters will affect the critical deposition velocity and thus the optimal pumping conditions.

Davel and Robinson (2003) reported the realities facing contractors in tailings disposal operations. Being perceived as the tail end of any mineral exploitation chain, the equipment available for such operations (pumps and pipes) does not always match the requirements.

A novel method that can provide more economical pump operations by increasing slurry concentration and reducing mean velocities whilst maintaining operational stability was first presented at PASTE 2005 in Chile (Ilgener, 2005). Although tailings disposal using high-density or paste systems consumes significantly less water, such technologies require large thickeners and the like, and have different operating parameters altogether. Therefore, it is unlikely that existing pumping operations, based on centrifugal pumps, will be converted to thickened tailings or paste technologies, unless significant economic drivers are present. However, the proposed novel control philosophy can be retrofitted to all types of existing pump operations.

8.1 Overall system approach

The proposed novel control philosophy is based on the ability to measure reliably the in situ condition of the sliding bed or stationary bed at the invert of the pipe. The tailings disposal system can then be operated over a wide range of solids tonnage from the plant, with the operating conditions being continuously controlled to remain at the economic optimum associated with the increased slurry concentration and at a decreased transport velocity.

The in situ measurements would take into account the combined properties of all the solids in the pipeline, and thus would not be based only on the initial test work data used for the original design of the tailings-disposal pumping system. The effect on the critical deposition velocity of all potential variations in the slurry properties would be measured on-line during pumping operations, as mentioned above.

The new control strategy will increase the operating envelopes and actual duty points of the pump/pipeline system. Current installations would have to be adjusted to maximise the economic benefits attainable. This modification could be co-funded by the South African electricity supplier, Eskom, which has structures in place to support such initiatives financially by setting up individual ESCOs (Energy Savings Companies). Contracted universities would establish a baseline power consumption before any slurry flow optimisation would be implemented (Eskom, 2004). Thereafter, they would monitor savings due to the flow optimisation initiative in order to quantify the overall impact of the reduction in power consumption.
8.2 Pipeline efficiency

If the thermal sensors prove to be able to operate reliably under all process conditions with acceptable wear rates, they can be integrated into an on-line slurry control and optimisation strategy as follows:

One set of thermal sensors will be installed near the pump station to detect any sudden change in settlement behaviour before the material has been pumped through the pipeline. This set will respond in good time to any effect due to any temporary presence of coarser particles. A second set will be located towards the end of the pipeline where gradual settlement of selected particles may occur while they are passing along the pipeline.

If both thermal sensor sets indicate unwarrantedly high velocities, the pump speed can be gradually reduced to within acceptable, preset limits. The level in the mixing tank will increase, and additional wasteful dilution water will be reduced.

The slurry relative density will therefore gradually increase as it is assumed that the duty tonnage remains constant in this case. Eventually, a new stable operating point will be achieved at a reduced volumetric flow rate, but at a higher slurry density to maintain removal of the tonnage supplied.

A schematic of the proposed control philosophy is presented in Figure 14 below.

Figure 14. Proposed utilisation of thermal sensors to detect sliding bed velocities and thus reduce water and energy consumption

The concept of using thermal sensors, which were not originally designed to be installed flush with the pipe wall or at the invert of a pipeline and which are now located strategically along the entire pipeline, and of using their signals as control parameter to optimise flow conditions, is covered in the South African Provisional Patent...
8.3 Pump efficiency

After the flow rate has been adjusted for optimal flow conditions, the pumps may no longer be operating near their best efficiency point (BEP) for that particular slurry density as the new operating point may fall outside the BEP. As part of the transition from conventional, un-optimised slurry pumping operations to the new approach, pump speed ranges may have to be adjusted to provide the hardware to be able to operate at the desired new flow rates.

The overall energy savings will have to be evaluated on a holistic site-specific basis, including the savings in the water return pipelines from the dams due to the higher tailings density, before the pump specifications are adjusted.

8.4 Water and energy costs

The incentive to conserve water and energy varies due to regional supply and demand situations, existing infrastructure and environmental considerations. These external factors can be integrated into the slurry flow optimisation strategy by defining application-specific preferences, i.e. using either water or energy as the major driver for slurry optimisation. Alternatively, the potential credits obtainable by reducing current levels of consumption can be factored into the actual cost of water and energy to assist the control logic in deciding on the most economical operating point. Irrespective of the type of incentive, the on-line detection of the critical deposition velocity remains crucial for tailings disposal, when pumped either in a slurry form or as thickened tailings, or even as paste.

8.5 Data processing for decision-making on optimal flow conditions

The slurry flow control and optimisation strategy is part of the CSIR’s ‘Smart mine’ initiative. The overarching principle is based on the process outlined by Bellinger et al. (2004), linking Data, Information and Knowledge to create Wisdom (DIKW) within a matrix of improved understanding and connectedness. Raw Data measured at the pipe invert is meaningless, unless it is converted into related flow conditions and linked to system parameters to provide Information. This information updates existing information in a database containing the pump and pipeline performance history, as well as practical and technical boundaries. To maximise the information based on measured data, any particle size distribution information that may become available from routine sampling a few days after the tailings have been pumped should be added to the information database when it becomes available.

Processing all the information available quantifies overall patterns to create detailed Knowledge about the actual tailings system behaviour in detail and the related conditions at the invert of the pipeline. This is almost like using the existing pumping operations as an ongoing full-scale test set-up, with the thermal probes replacing transparent viewing sections and the time-intensive observations by an operator for each operating point.
Applying the fundamental principles of pipeline transportation to the information database, and considering environmental aspects, legal frameworks and the fundamentals of sustainability development, eventually culminates in Wisdom. If, at this high level, the indications are that the system is not operating optimally (including preferences set by the plant), the control logic will decide which operating parameters (density and/or pump speed and flow rate) need to be varied and to what extent in order to approach the most economical operating conditions. This overall “processing” is also shown in the schematic in Figure 14 above.

The pipeline system characteristics may require a certain amount of time until the new operating point has affected the reading of the flow sensor mounted towards the end of the pipeline. This delay will dictate the gradient at which parameters are varied to avoid unsteady conditions and ‘over-swings.’

While the system is adjusting to the new set point, continuous data acquisition and analysis thereof ensures a controlled change. The actual extent to which a slurry or paste system is equipped with appropriate hardware and control options to enable optimisation has to be balanced between potential savings and the risks to be avoided.

8.6 Immediate next steps

The existing short-length, small-diameter pipe loop for slurry and paste testing has been equipped with a feedback control loop to process the immediate output from any one of the thermal probes mounted at the pipe invert in order to control the actual pump speed and thus the system flow rate. The control set-point for the velocity at the pipe invert can be varied for various degrees of sliding bed movement, which can be steady and slow, or may alternate erratically between movements and stoppages, depending on the slurry/paste properties. Any gradual fine adjustments require time to stabilise. An alarm is, however, raised as soon as the onset of a stationary bed is detected; this then triggers an immediate, meaningful increase in the pump speed to reduce any built-up of stationary solids.

Once the feedback control loop parameters have been tuned, and auxiliary instrumentation such as slurry concentration, mass flow and power consumption have been linked to the data-acquisition system and have been calibrated, the small loop will be used to create relationship graphs for critical deposition velocities versus solids concentrations. This will cover tailings from the hard rock mining sectors, i.e. platinum and gold, as well as from soft rock mining sectors, such as coal (fly ash and fine coal slurries) and Kimberlite pastes.

During these tests, dilution water or dry solids will be added to the mixing tank while the loop is running at a stable operating point. Within a short period of time, the slurry composition in the pipe loop will have changed due to the addition of either dilution water or dry solids. In the short loop, this will have an immediate effect on the critical deposition velocity. The response time of the thermal probes and of the feedback control loop circuit driving the pump will be analysed and fine-tuned, and will be documented as part of developing and implementing the control methodology.
It is planned to do tests in longer pipe loops, with larger pipe diameters so that the probe size becomes relatively smaller in relation to the pipe diameter, thus creating a more focused zone of influence within the pipe cross-sectional area. These tests could be done with Paterson & Cooke in Cape Town as part of evaluating the overall methodology and to obtain new data for larger pipe internal diameters and to gain control experience with longer pipe loops.

8.7 Long-term implementation strategy

Endurance tests with the thermal probes to determine their calibration stability and performance under varying external temperature conditions will need to be conducted. Their slurry-specific wear rates and overall industrial suitability will need to be evaluated during further laboratory and industrial trial applications.

The Data, Information, Knowledge and Wisdom hierarchy will need to be established to provide a basis for decision-making. It is envisaged that a model will be developed to process actual data from the pipe loop and compare them with existing data from a database. The model will also have to be able to accept external factors, such as costs for energy and water consumption, to determine the most economical, yet stable system operating point. Such a model can be tested and verified by using it on the laboratory test rig with feedback control loop prior to implementation on a larger scale.

9 CONCLUSION

Various types of complex instrumentation have been developed in various parts of the world to measure critical deposition velocities. However, they are typically operated by skilled personnel in R&D environments and are not used in industrial plant operations.

The paper has described recent test work with the Transfelectron© instrumentation from Panametrics, which is a relatively mature instrumentation set-up with a user interface. Unfortunately, this instrument can only detect velocity or sliding bed behaviour at a distance of about 15% of the pipe diameter above the invert of the pipe.

For this reason, thermal probes, mounted directly flush with the pipe invert where they can detect the actual velocity at the pipe invert, were recently tested in the laboratory. Their quick and proportional response characteristics made it possible to develop a new philosophy for slurry flow control. This is part of an initiative to pump tailings at higher concentrations and at lower velocities than are currently being achieved. This will reduce overall water and energy consumption while still ensuring stable operating conditions without the risk of gradual pipeline blockages.

A feedback control loop is being installed in a slurry test rig to facilitate the evaluation of various thermal probes for establishing critical deposition velocity data, linking flow observations through transparent viewing sections to continuous signals obtained from these instruments. This will be done for a range of tailings compositions and solids concentrations to establish a reference database to be used later for control decisions.
Furthermore, the feedback control loop on the test rig will assist in developing an overall control methodology, based on preferences as to whether either water or energy is the main resource driver to optimise slurry flow conditions. The decision-making optimal control parameters will be based on historical data and a live database to obtain the most economical operating point for any actual slurry or paste composition.

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