Cyanide control in the metallurgical process of gold extraction in AngloGold (S.A.)

by B.J. Vorster* and S.R. Flatman†

Synopsis

AngloGold South Africa region currently consists of twelve gold plants. These plants use a combined total of $20 million of cyanide per annum. Of this, the major portion (60%) is consumed at two Ergo dump retreatment plants. Historically the primary motivation for cyanide control at Ergo has been one of leach/cost optimization. However, more recently, with the increased public awareness of cyanide in the environment, a secondary but increasingly important motivation for control has been to ensure that only the minimum amount of cyanide is added to the process whilst not compromising leach performance.

Following a brief overview of the Ergo process, the methodology in determining the amount of cyanide to be added is described. The paper then traces the developments in cyanide control from very basic manual systems to the current automated control system. In line with the increasingly sophisticated control systems, developments also took place in regards to the method of cyanide analysis. The development of these analysers is also discussed. Whilst cyanide is one of the major drivers, if not the major driver of gold dissolution, it cannot be viewed in isolation particularly with respect to the relationship between cyanide and oxygen as ascertained from the Elsner's well-known equation. Consequently, in order to control cyanide addition, knowledge of the relative cyanide/oxygen profiles is necessary. Various means investigated at Ergo for pulp oxygenation have therefore been included for the sake of completeness. Finally a comparison is made of the control achieved from the current system compared to the original manual system.

The knowledge and experience gained at Ergo is now being used to draw up guidelines for the installation and optimization work at the other AngloGold plants. The net effect of this will be reduced cyanide consumption for the region, which also, apart from the obvious economic benefit, translates into a reduced environmental risk.

Introduction

The ERGO CIL plant treats 3 million tons per month reclaimed by hydraulic mining from surface slimes dams. A mix of up to 12 individual dams is piped in 6 lines feeding the plant. The leach circuit comprises 22 tanks with a total volume of 44 000 m^3 in two parallel streams that allows for a total retention time of 7 hours.

Calcium cyanide is added at an addition rate of approximately 350 g/t. Due to the large tonnage multiplier, this equates to approximately 1 000 (as 100% NaCN) tons of cyanide per month representing approximately 25% of the total operating cost. Consequently a large amount of developmental work has been conducted at Ergo in regards to determining the optimum cyanide addition and to minimizing deviations from the target addition.

More recently, increased environmental awareness has further focused on the necessity for tight control in order to minimize the amount of cyanide added to the process and thus in residue streams whilst not compromising leach performance.

Determination of the optimum cyanide addition

Due to the high tonnage and commensurate short leach residence time, the kinetics of the leach reaction, whilst important in any operation, are particularly important at Ergo because the cyanide concentration is not high enough and insufficient time exists to dissolve the gold. The situation is illustrated in Figure 1.

From Figure 1 it is noted that the optimum cyanide addition rate exists where the marginal gold revenue is equal to the marginal cyanide cost. To the left of this point the marginal revenue from the additional gold exceeds the marginal cost of cyanide, calling for the addition of more cyanide. To the right of this point, the opposite holds true and marginal losses are incurred. This optimum cyanide rate is found in practice by monitoring the response of the leachable gold losses determined through daily laboratory leaches (500 g/t NaCN, 4 hours) and correlated with the plant cyanide addition rate.

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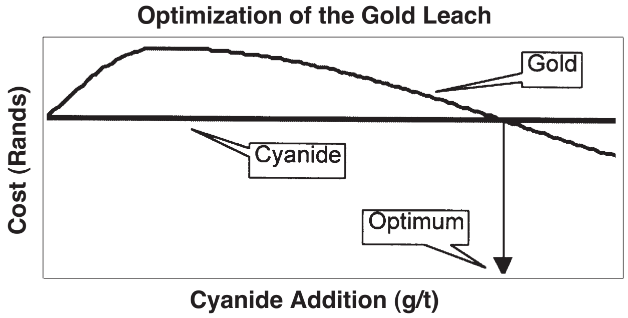

Figure 1—Marginal gold revenue versus marginal cyanide cost

Influence of oxygen

Whilst cyanide is one of the major drivers if not the major driver of gold dissolution, it cannot be viewed in isolation particularly in respect to the relationship between cyanide and oxygen derived from Elsner's equation:

$$4\,Au + 8\,CN^{-} + O_2 + 2\,H_2O \Rightarrow 4\,Au(CN)_2^{-} + 4\,OH^{-}. \qquad [1]$$

From the Equation, it is apparent that both cyanide and oxygen are required in an aqueous solution in order to leach gold. For the leaching of pure gold, the stoichiometry of Elsner's reaction gives the required molar ratio of free cyanide to oxygen as 8:1 (or $6^1/_2$:1 when expressed as a mass ratio). Since cyanide is the more expensive reagent, it is desirable from a financial point of view to ensure that cyanide is the rate-limiting reagent. Hence a cyanide-to-oxygen ratio that is less than the determined 'stoichiometric' ratio should be maintained throughout the tank farm. Maintaining a constant ratio of the reagents in each tank may only be achieved by ensuring that the cyanide and dissolved oxygen profiles relate to one another.

Referring to Figure 2, the dissolved oxygen concentration (DO) at the Ergo CIL plant rises from about 6 to 8 ppm in the top tank to about 18 to 20 ppm in the second to fourth stages after which it decays to about 9 ppm in the final stages. The low DO content in the first stage is indicative of the high initial oxygen demand of the material. Considering this in conjunction with the stoichiometric ratio, it is clear that at least two cyanide addition points should exist with the first two stages being the obvious choice so as not to compromise leaching efficiency. Furthermore, the highest cyanide concentrations will exist but should be controlled in the second to fourth stages since this is where the maximum DO levels are. Comparing the cyanide profiles obtained for single stage and dual stage cyanide addition, the advantage of the latter is that it ensures that the cyanide and oxygen profiles follow one another more closely such that a more consistent ratio is maintained. The various means investigated to increase the circuit DO are discussed later.

Sampling system

Having established a control philosophy, the next challenge is implementation. The obvious starting point is to obtain a representative sample. In contrast to the pump/filter system used in many operations and their associated disadvantages, Ergo has found considerable success utilizing pipe samplers to produce a continuous clear solution sample. See Figure 3.

The samplers consist of a 6 m*15 mm steel pipe fitted with a 1 m*100 mm filter bag pulled over a rolled up piece of linear screen cloth to provide a void for the clear solution. Due to the difference in relative densities of the bulk slurry and solution inside the pipe, solution is forced up a 6 mm line fitted inside the pipe to provide a sample. A pulse of compressed air every 2 minutes for 10 seconds inflates the bag that breaks up the filter cake on the bag while pushing the filtered solution through the sample line.

Having obtained a solution sample and analysed it for cyanide, the result is used to control cyanide addition to the leach. Various systems of increasing complexity have been developed at Ergo over a period of time. The development of these control systems from manual control to the current system is detailed below.

Control systems

Manual control system

The original cyanide control system was manual whereby the operator adjusted the flow of cyanide to the process based upon the results of a manual titration performed hourly. Some automated assistance by means of a flow-controlled

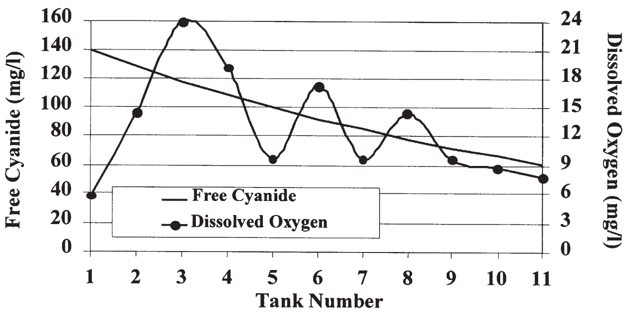

Figure 2—Cyanide/oxygen profile at Ergo CIL plant

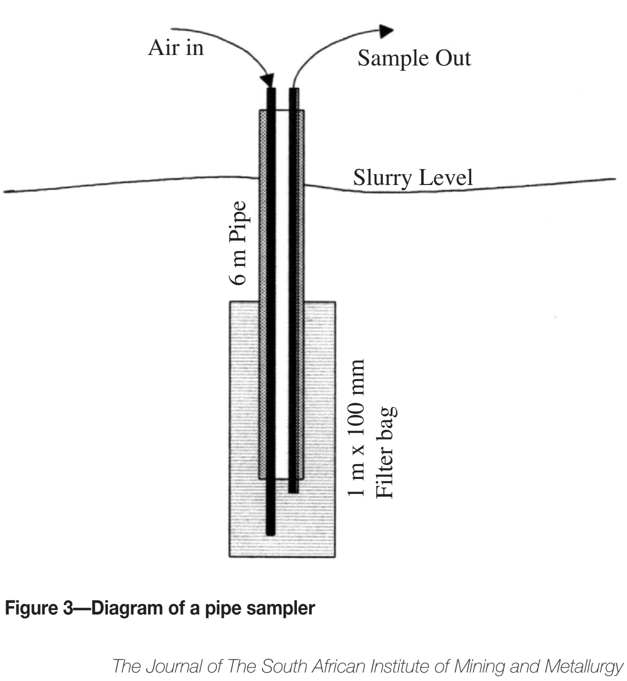

Figure 3—Diagram of a pipe sampler

valve was employed that dosed the cyanide at a predetermined volume based on the operator set point as shown in Figure 4. This made it easier for the operator so he/she could calculate a required flow for the specific tonnage being processed through the plant to achieve a required addition rate.

Variable tonnage control system

The major drawback of the manual system was that operator action was too infrequent to keep up with the rapid changes in throughput as shown by the graph in Figure 5. Since these variations in throughput were caused by external operations and were not under the control of the operator, he/she would not always be fully aware of the extent of the changes occurring until a response was seen on the cyanide concentration.

The next stage of the optimization process involved the integration of tonnage measurement utilizing the existing mass flow system and a PLC (see Figure 6). This feed forward system now handled variations in throughput whilst still maintaining a fixed addition rate. As opposed to manual control whereby the operator was forced to estimate the effect of tonnage variations on the cyanide decay curve, the process was now automatic. All that the operator needed to do was stipulate a required addition rate. The PLC then calculated a cyanide flow rate required to achieve the addition rate based on the following formula:

$$Set\ Point_{(l/h)} = \frac{Mass_{(tph)} * Set\ Point_{(g/t)}}{Cyanide_{(\%NaCN)}} \qquad [2]$$

Set Point (l/h)	Volume of calcium cyanide required in litres per hour
Mass (tph)	Mass flow of incoming material to the plant in tons per hour
Set Point (g/t)	Estimated cyanide consumption for material being treated
Cyanide (%NaCN)	Active content of calcium cyanide expressed as sodium cyanide

On-line cyanide analyser control system

Whilst the inclusion of tonnage measurement represented a significant improvement in the overall control of cyanide, periods of poor control still regularly occurred. Continuous changes in the cyanide demand of the feed material were identified as adversely influencing the cyanide control. The operator's actions based on an hourly titration were too slow or inconsistent to adequately compensate for these variations in cyanide demand. The manual titration of the operator was therefore replaced with an on-line cyanide analyser. This analyser provided regular and repeatable data around which a cyanide control system was designed to control to an operator-specified cyanide concentration as shown in Figure 7.

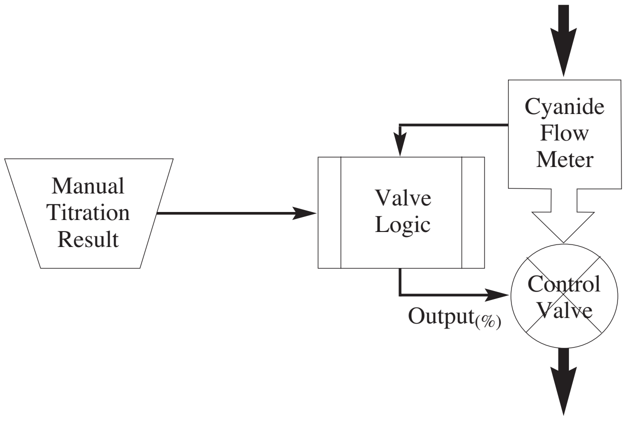

Figure 4—Manual control of cyanide into the process

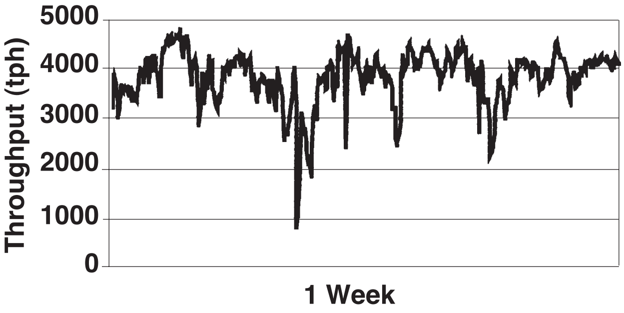

Figure 5—Plant throughput in dry tons per hour

The feedback controller then adjusted the cyanide flow to correct for any deviation from set point caused by changes in demand. A significant amount of work was done to find better analysers to give faster analysis time so that control could be improved. These analysers are discussed in detail later.

Advanced control system

Previously, when the density of the slurry decreased, a lower cyanide concentration would result due to increased dilution. An algorithm was therefore installed to pre-empt these changes by making use of the formula shown in [3]:

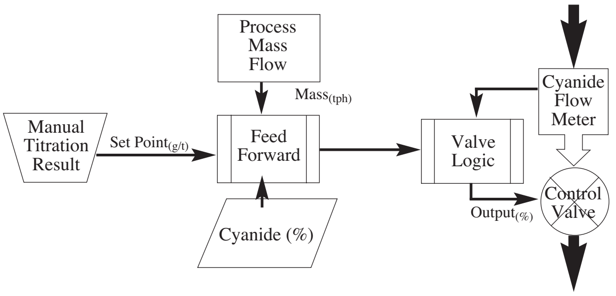

Figure 6—Variable tonnage control system

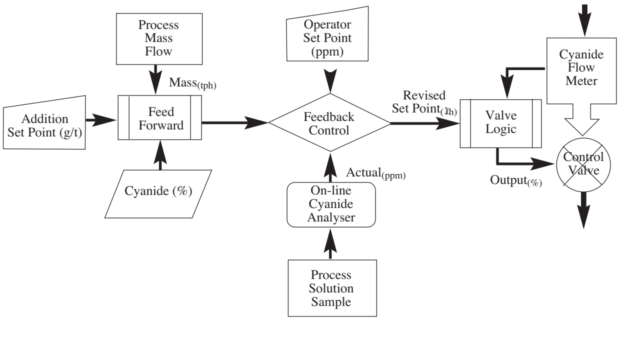

Figure 7—On-line cyanide analyser control system

$$\text{Density Correction Factor} = \frac{\left(2.7 \pm Density_{(Reference)}\right) * \left(1.7 \pm Density_{(Actual)}\right)}{\left(1.7 \pm Density_{(Reference)}\right) * \left(2.7 \pm Density_{(Actual)}\right)} \quad [3]$$

The algorithm now compensates for decreases in concentration by adding additional cyanide. In practice it was found that applying 50% of the calculated factor to the cyanide flow yielded the best response for a steady cyanide concentration. Returning to the main control system intervention by the metallurgist was still required at regular (daily) intervals to fine-tune the addition rate used by the feed-forward controller to ensure the stability of the system. Realizing that the information used to do this was available in real time from the instrumentation a self-optimizing system was devised. The comparator in Figure 8 feeds back a fraction of the error that exists between the estimated addition rate and the actual addition rate at a regular interval so that the feed-forward always uses the correct multiplier to calculate the required flow rate. It does this very slowly so as not to cause oscillation in the feedback control loop or to interfere with the overall control system.

Dual stage cyanide control system

Despite the various improvements made to cyanide control, a major drawback still existed with the single-stage addition system. It was found necessary to maintain a higher than metallurgically optimum cyanide concentration in the first leach stage to ensure that sufficient residual cyanide existed to fully utilize the residence time available. The cyanide consumption was high due to the low dissolved oxygen levels in the top tank resulting in cyanicides still being available to complex the cyanide.

Figure 9 illustrates that the first stage cyanide concentration was reduced after a secondary dosing point was installed to make up the difference required to ensure the desired final stage cyanide tenor. The cyanide analyser monitoring the last leach stage was relocated to analyse the second leach stage and a separate feedback-only control system was installed. The first leach stage is run at a fixed cyanide concentration of 100 ppm [CN] while the second stage is varied to obtain the correct final stage cyanide tenor. The second stage typically runs at about 110 ppm [CN]. A closer correlation was now achieved between the desired cyanide and oxygen profiles resulting in a reduction in cyanide consumption of approximately 5–10%.

Controller hardware optimization

Instrumentation expertise was called upon to optimize the hardware installed for the dual-stage cyanide addition systems. Using extensive modelling and the Pro-Tuner software, the system was successfully commissioned in 1999. The controller settings were based on models created on what was later discovered to be incorrect assumptions. After getting a better understanding of the process, in-house tuning greatly improved the controller performances on both primary and secondary controllers. It was found that high gain (high proportional) and short reset times (low integral) were used, as would be the normal trained response of any instrumentation technician. The setting cause a typical $^{1}/_{4}$ wave damping that results in a significant overshoot in a slow response system, as is the case here. It winds up rapidly and becomes unstable after the smallest upset. Using reset (integral) times equivalent to the tank's retention time had a significant stabilizing effect.

An inherent feature of the controller design was the separated feed-forward and feedback components. This resulted in corrective action only affecting the feedback component. Any long duration error that would require a change to the addition rate causes instability and could only be corrected manually. In an attempt to reduce human intervention a method to automate this action was investigated and the result was the self-optimizing tool discussed earlier.

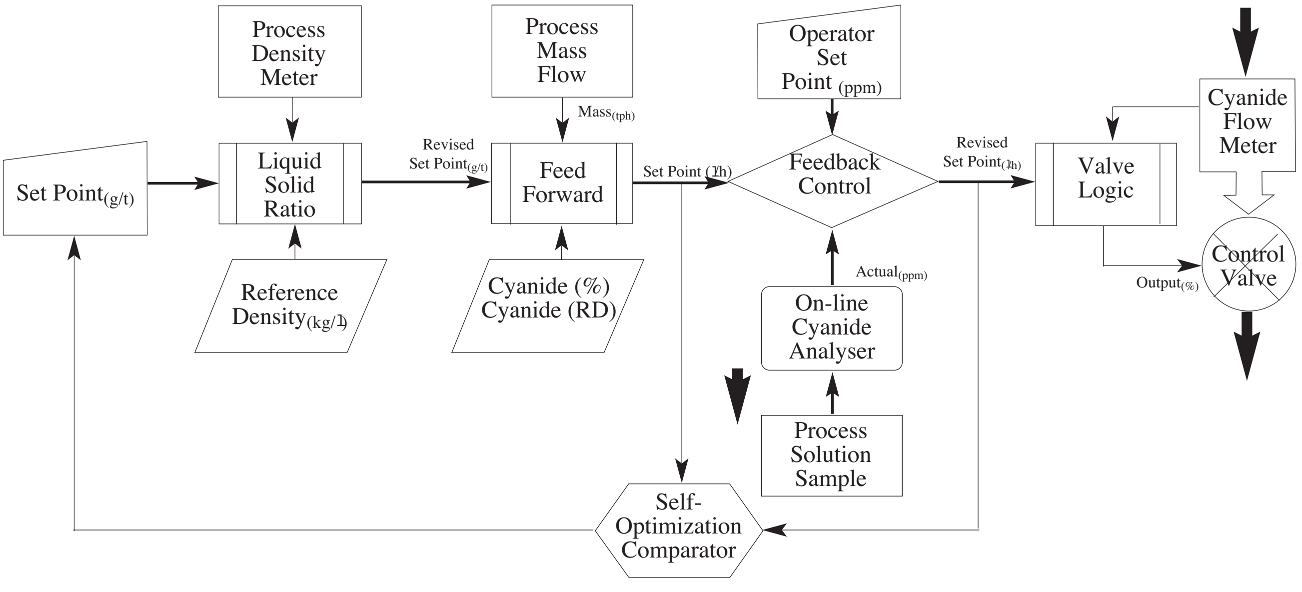

Figure 8—Advanced control system with density compensation and self-optimization

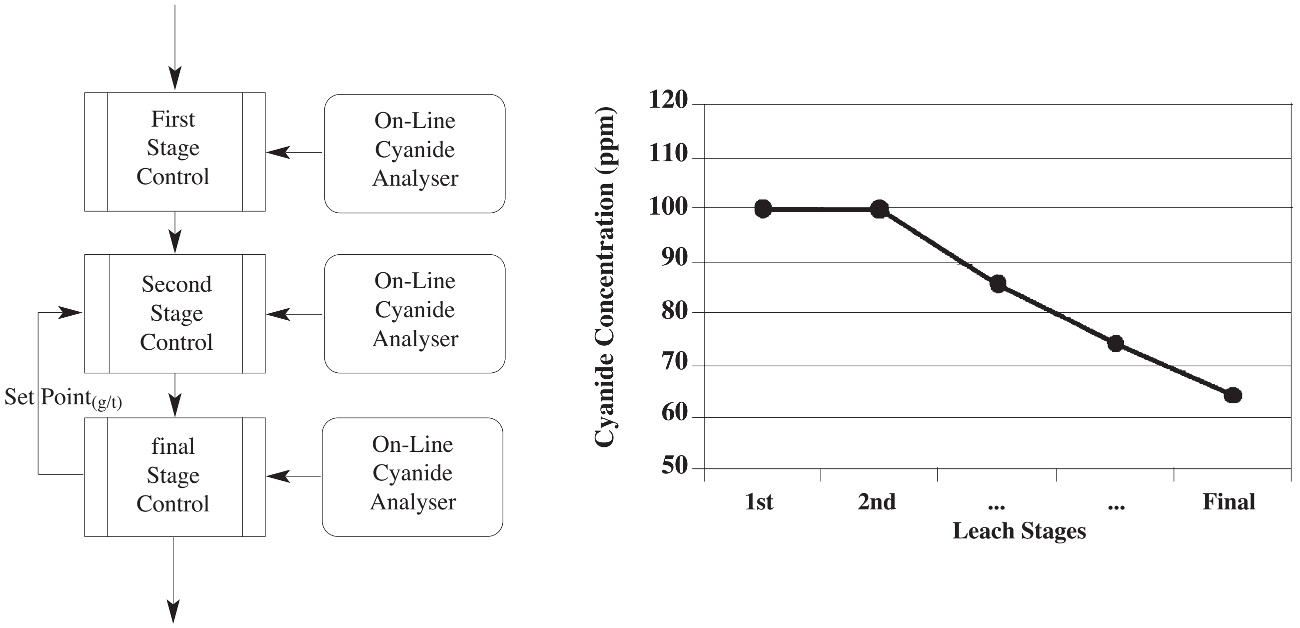

Figure 9—Dual stage cyanide control with final tenor feedback

On-line cyanide analysers

In line with the developments in the cyanide control system developments were also made in the cyanide analysers used to provide the control signal. These initiatives are discussed below and later compared in a Table (see Table I).

Kayton

This machine was developed by Anglo American Research Laboratories to perform on-line analysis of cyanide, pH and gold in solution every 40 minutes. The results were then wired to the PLC for use in whatever control system was implemented there. It was designed for 8 sample streams but only 4 were used to improve the sampling frequency to 40 minutes. The first and last leach stages on both treatment streams were analysed. Cyanide detection was by means of a potentiometric analytical technique using an automated titration with silver nitrate. This became the standard analytical technique used in nearly all cyanide analysers for the next 10 years. The development of improved commercial analysers by other companies combined with the Kayton's uniqueness leading to problems with support and spare components eventually prompted a decision to replace it with one of the commercially available analysers.

Cascon T

An Applikon 2015 cyanide analyser was selected for the first leach stages and an Applikon 2011 cyanide analyser on the last leach stages. The new control system was collectively referred to as the Cascon T. These Applikon cyanide analysers also use a potentiometric analytical technique to detect cyanide. Each device can analyse two sample streams at around one analysis in 10 minutes. Changing the software later enhanced them so that a sample could be analysed in less than 3 minutes.

Teklogic

The ERGO sister plant (Daggafontein) installed Teklogic (TAC) cyanide analysers. The Teklogic is also a potentiometric type analyser but includes as an option cyanide control. Teklogic analysers are used worldwide on AngloGold plants.

Anatech

An Anatech Flow Injector cyanide analyser was also tested at the CIL plant, as its potential to improve cyanide control due

Table I

Comparison of successive cyanide analysers investigated

Advantages	Disadvantages
Kayton First generation on-line analyser Capable of analysing 8 streams	One of a kind that became obsolete with no spares being available. Slow sample frequency of 40 minutes
Cascon T Commercially available Robust and reliable Upgraded to increase sampling frequency to under 3 minutes per sample	Initial sample frequency low at 10 minutes per sample prior to upgrade. Regular maintenance required
Anatech Flow Injector Fast analysis time of 90 seconds per sample Built-in calibration and quality checking Capable of analysing six streams High precision and accuracy No cross-stream contamination	High running costs Complex machine with multiple reagents High maintenance and maintenance cost Specialized maintenance High downtime due to above No signal output to PLC
Mintek Cynoprobe Very fast analysis time of 60 seconds Virtually no maintenance No reagents used for analysis	Single stream capability only Cannot be duplexed for multiple streams

to its high sampling frequency of one in 90 seconds was appealing. The analyser uses a colorimetric technique to detect the cyanide in a chemically prepared solution. The device was decommissioned in favour of the existing titrators that are less complex, have better availability, and are cheaper to operate.

Mintek

A Mintek Cynoprobe was also tested. It uses an amperometric technique to detect the cyanide and requires no reagents in the process. With a sample analysis time of less than 60 seconds and robust enough for plant conditions, this unit is the preferred analyser for new installations. However, it should be noted that this unit is newly developed. With the remaining life of ERGO it is not viable to replace the existing titrators but other plants that have a longer remaining life could pursue this option.

Oxygen equipment

As discussed earlier the dissolved oxygen concentration in the pulp also influences the cyanide tenor and so, whilst the primary focus has been towards cyanide control, considerable work has also been performed toward efficient oxygenation of the pulp. More recently this work has been performed at Ergo's sister plant Daggafontein. It should be noted that compressed air can only oxygenate to a dissolved concentration of approximately 8 ppm. Due to the high oxygen demand and high throughput at Ergo, gaseous oxygen is used to increase the concentration to a target of 20 ppm. Ergo's experience with oxygen injection equipment are detailed below.

Perforated ring

A donut shaped perforated pipe was fitted inside the leach tank just above the flat bottom. It was not very efficient and was maintenance intensive. Different types of material, including porous cast pipe and plastic hoses, were evaluated over time. The leach tank had to be taken off-line to do maintenance on the system.

Lances with ceramic tips

Lances measuring 15 mm in diameter fitted with ceramic tips were inserted through the tank shell about $^1/_2$ m from the bottom. The tip has a 6 mm hole and a taper rod that can be manually adjusted from outside the tank. Ten lances are required on the first leach tank to achieve 8 ppm dissolved oxygen in 40 minutes and is indicative of the high oxygen demand of the material. The second leach stage easily achieves a dissolved oxygen concentration of up to 20 ppm. A system was developed to change these lances while the tank is on-line with the use of an isolation valve that the lance passes through. This system is still in use at the ERGO CIL plant.

Lances with variable gap tips

Alternative lance tips were evaluated that have a spring-loaded inverted cone-shaped tip that automatically adjusts with the oxygen flow. They are claimed to be more efficient and feature an automatic shut-off to prevent slurry choking up the lance if the gas supply stopped. These tips were unattractive because they lasted one month compared to the six months achieved by the fixed type.

Water nozzles

The Daggafontein plant evaluated water nozzles that use water at 6 bar and gaseous oxygen controlled up to 9 bar injected into a small reactor that allows the emulsion formed to escape sideways into the slurry. They are more efficient and have finer bubble dispersion and less bubble agglomeration. It requires other auxiliary equipment including a source of clean pressurized water and various control valves and sensors. They are well suited to yield high dissolved oxygen concentrations quickly and efficiently but water-use limits the number of units that can be installed in the leach train.

Shear reactor

A proprietary high shear reactor was tested at Daggafontein. The device injects gaseous oxygen into a special, formed ceramic reactor through which slurry is pumped at 6 bar. Oxygenation is achieved through cross-shearing of the oxygen caused by the rapid flow direction changes in the specially shaped patented reactor. With the existing lance system already achieving good results and being unable to detect any improvement, the additional costs of running the unit could not be justified.

EDR

This device used is similar to the high shear reactor but operates at a lower pressure. Oxygenation of the slurry is achieved by injecting gaseous oxygen via a perforated ceramic venturi insert and making use of the formation of turbulent eddy currents in the slurry pumped through the device. The device is currently on trial runs at Daggafontein.

Results

As can be clearly seen from Figure 10, the various initiatives undertaken at Ergo have resulted in a significant improvement in cyanide control. Whilst an exact financial quantification of the benefits is complicated by changes in the feed mix and mineralogy particularly as regards cyanide and oxygen demand, a conservative Figure of US $1 million per annum has been estimated. This value has been calculated from a combination of savings in cyanide due to reduced over-dosage and reduction in leachable gold losses due to under-addition. Over and above the economic considerations, the improved cyanide control has resulted in a reduced cyanide addition which inevitably contributes towards reduced environmental exposure.

Conclusions and recommendations

A conventional gold plant should be able to achieve acceptable control of cyanide to the process by using the system depicted in Figure 11. Here the output from the feedback controller that corrects for deviations in the cyanide concentration is taken as the process demand. This demand is then manipulated by applying a mass flow percentage in a basic feed-forward calculation that, in turn, provides the set

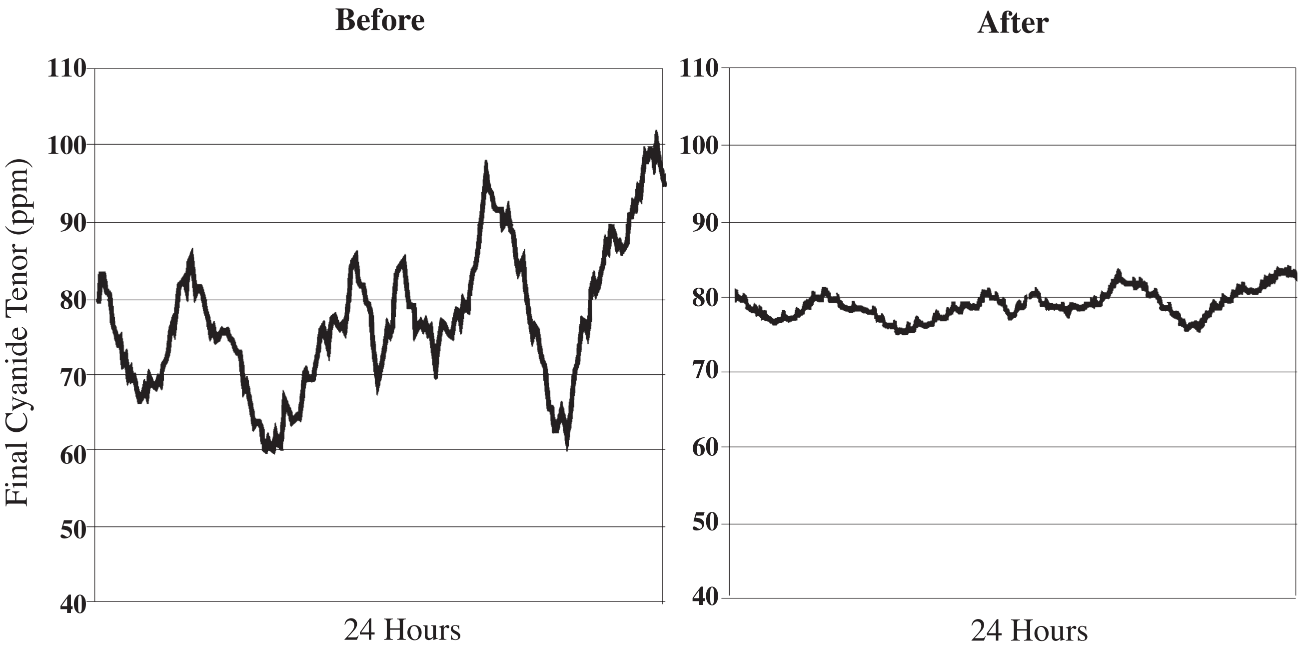

Figure 10—Manual and automated cyanide control comparison graphs

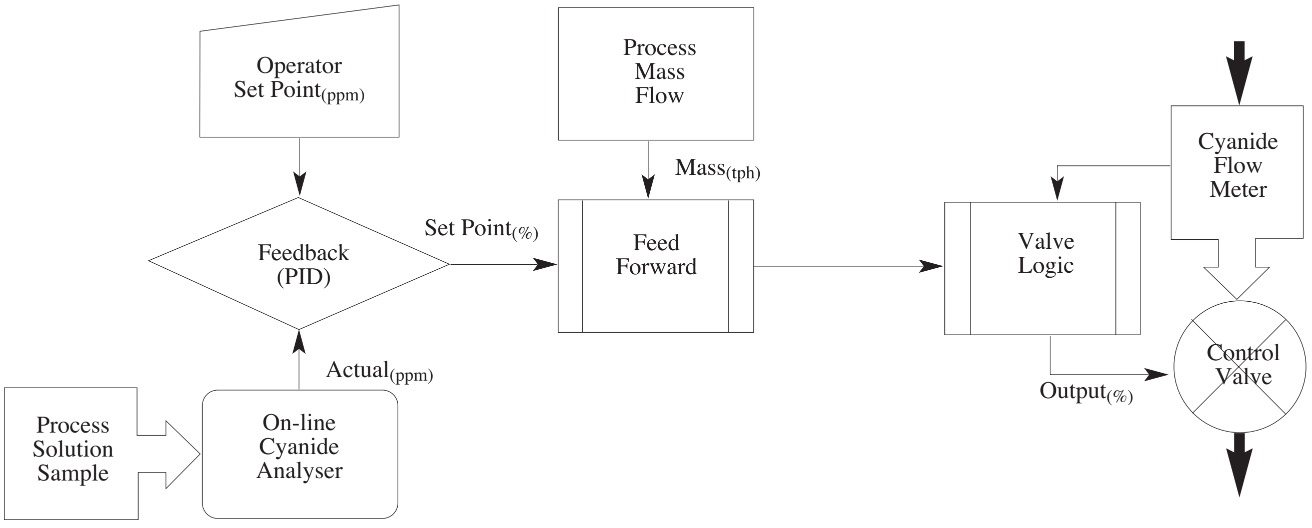

Figure 11—Minimum implementation automated cyanide control

point for the cyanide flow controller. The system is self-adjusting to changes in the process demand provided that the PID loop is correctly tuned for very slow process dynamics.

The on-line cyanide analyser should be able to sample at least 8 times in a period equivalent to one leach tank's retention time with 99% repeatability. The more recent amperometric type analysers are well suited for this application. If the control band is wider than +/- 10% then advanced system add-ons should be investigated such as a system that compensates for changes in slurry density.

Multiple cyanide dosing stages should be investigated where the cyanide concentration exceeds the optimum as described by the cyanide:oxygen ratio of 8:1 expressed as molar ratio. Oxygen addition is recommended in preference to air where leach kinetics is a constraint.

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Tukkies Mining Engineering awarded Fulbright scholarship*

Dr Roger Thompson, Associate Professor in the Department of Mining Engineering at the University of Pretoria, was awarded a prestigious Fulbright Research Scholarship. The Fulbright Programme is recognized as the US Government's flagship programme in international exchange.

The annual award of a Fulbright Commission for Educational and Professional Exchanges' South African Researcher Scholarship is administered by the bi-national Fulbright Commission and candidate selection is finally ratified by the J. William Fulbright Foreign Scholarship Board, appointed by the President of the United States.

Established in 1945 by freshman Senator J. William Fulbright, the programme was aimed at developing 'mutual understanding between people of the United States and the people of other countries of the world'. Dr Thompson will work in the United States with the Centres for Disease Control (CDC), National Institute of Occupational Safety and Health, Spokane Research Laboratory (SRL), together with the Western Mining Research Centre, at the Colorado School of Mines (CSM). His project on characterizing mine haul road functional defects as a causal factor in truck driver jolting and jarring injuries fulfils Fulbright's requirements of having benefit and application in the mining industries of South Africa and the United States.

An interdepartmental research field in mine haul road design and management was established together with Prof. Alex Visser from the Department of Civil Engineering in the mid-1990s and Dr Thompson's research in the United States builds on their internationally recognized research. Over 34 peer-reviewed and conference papers have been published at leading local and international conferences and symposia. The results of the research have already been adopted and applied, not only in southern Africa, but also internationally. Projects in Botswana, Namibia, the United States and Indonesia have been undertaken, and more recently, he has been invited to co-author a book on mine road design with academics in Canada.

Explains Dr Thompson 'the research programme with SRL and CSM fulfils the requirements of the Fulbright programme in the sense that technology transfer in mine haul road design, specifically haul truck mine road interaction, is two-way and has benefit and application in the mining industries of both countries'.

'Mine haul trucks are amongst the largest wheeled vehicles on earth with a mass of over 560 tons, tyres of 2,6 m in diameter and 1 m width. It is a varied, challenging and dynamic field and the results of the work are particularly important in the light of the ever-increasing size of trucks, road performance problems and the formidable health issues surrounding driver exposure to poor ride quality'. ◆

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