



# Innovative process control technology for milling and flotation circuit operations

by G.C. Smith\*, L. Jordaan\*, A. Singh\*, V. Vandayar\*, V.C. Smith\*, B. Muller\*, and D.G. Hulbert\*

## Synopsis

Process control applications in the minerals processing industry have grown extensively over the years due to the many benefits derived, both financially and operation-wise.

Although control theory is widely known, conventional control does not address many of the problems posed by minerals processing circuits. Some of these problems include interactions between process units, large dead times, few and sometimes unreliable measurements of process variables, non-linear systems, disturbances entering the process, processes with varying dynamics, and many more.

For the past 26 years Mintek has been active in the field of providing specific, customized solutions for the minerals processing industry. This paper focuses specifically on applications in milling and flotation control. The underlying control principles have been applied to a wide range of other processes including submerged arc furnaces. Advanced control application is implemented on a common advanced control platform, called the PlantStar.

Much innovation has been brought to the fore in terms of adapting theoretical techniques and developing new methods to resolve specific milling and flotation circuit issues by using process control. The general approach adopted by Mintek when implementing advanced control is to enforce stabilization of the process as a solid foundation for optimization strategies to be built upon. In doing this, a robust control solution is presented, and the end result is flow and level stability, better product quality regulation, increase in throughput and a stable feed to downstream processes.

The MillStar advanced milling control system ensures that the milling circuit is at all times easy to operate while achieving optimum product quality and throughput. Stabilization should include product size regulation and sump level control. Another important aspect of stabilization control is the handling of milling circuit constraints without introducing cyclical behaviour and with minimal disturbance to the final product quality. Process constraints may include factors such as process water limitations, cyclone feed density, and cyclone underflow angle. An optimization strategy should be developed to increase the mill throughput without affecting product quality or introducing mill overloads. The relationship between solids feed and power draw is examined and manipulated for optimization.

The interactive nature of flotation circuits and the presence of recirculating streams tend to make satisfactory control almost impossible with conventional techniques such as PI (Proportional plus Integral) or PID (Proportional, Integral and Derivative) control. The FloatStar Level Stabilizer simultaneously considers all the flotation levels in a circuit by use of a multivariable algorithm, and takes compensating action in anticipation of disturbances. The FloatStar Flow Optimizer is an optimization strategy that controls the concentrate flow rate between various sections of a flotation circuit (e.g. Rougher → Cleaner; Cleaner → Recleaner). By controlling the concentrate flow between the sections, the mass pull, circulating loads and residence times of the circuit can be stabilized, thereby enhancing the performance of the flotation process. Optimizing grade and recovery are coupled with the dynamic optimization of circulating flows. The FloatStar Grade-Recovery Optimizer will maximize the grade in a section, whilst ensuring that recovery or any other process specific limits remain within predefined limits.

With successful applications on several milling and flotation plants worldwide processing amongst others PGMs, gold, copper and nickel, Mintek has shown that it is a leader in milling and flotation control innovation

## Introduction

Process control applications in the minerals processing industry have grown extensively in recent years. Stronger competition, stricter environmental and safety regulations, and ever-changing economic conditions have fuelled the drive for attaining greater control over processes. Furthermore, modern applications have become more difficult to run because the trend in plant process design is towards larger, more flexible and integrated plants, with less surge capacity between process units. Such processes are subject to large interactions between adjacent process units, and process stability is difficult to achieve. With the modern emphasis being on product quality, safety and reduced environmental waste, process control has advanced to meet the requirements of the minerals processing industry.

Control theory and process automation equipment are widely available and have been implemented in the minerals processing industry with varying degrees of success. Most process control theory has been fuelled by the petrochemical industry, where there are very tight constraints on operating conditions and emissions. Petrochemical processes are typically very well instrumented and relationships between input and output variables are well defined. Thus, conventional process control theory works well in this environment.

In the minerals processing industry, process control is challenged by many factors. Due to the abrasive nature of slurry streams, it is often difficult to find instrumentation that can, firstly, endure the abrasive conditions and secondly, deliver a good quality measurement. Therefore, instrumentation is relatively basic

\* Measurement and Control Division, Mintek, Randburg, South Africa.

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and many process conditions are completely unknown, and have to be inferred or estimated from available instrumentation, often with large errors and low confidence.

Apart from sparse and unreliable instrumentation, minerals processing circuits also suffer from many other problems including interaction between process units, large dead times, slow communications between field units and the controllers, non-linear systems, disturbances entering the process, processes with varying dynamics, and many more. Conventional process control theory does not always cater for these conditions.

For the past 26 years, Mintek has been active in the field of providing specific, customized process control solutions for the minerals processing industry. In particular, milling, flotation and furnace control systems have been developed and these have been implemented at over 100 sites worldwide. This paper focuses specifically on applications of Mintek's control in the milling and flotation industry.

## Mintek's control philosophy

### Understand the process

An essential first step in implementing a process control application is understanding the process. Knowledge of the process enables an appreciation of physical process constraints, what the key performance indicators of the process are, and which variables can be adjusted to achieve the desired performance within the process constraints.

### Stabilization before optimization

Mintek adopts a prudent methodology when implementing process control solutions. The 'stabilize before you optimize' approach is used. The control hierarchy (see Figure 1) has its foundations in good infrastructure (instrumentation and actuators) and stabilization control. Without the necessary stabilization of the process, it is near impossible to successfully optimize the process.

Mintek has developed a suite of stabilization controllers, specifically designed to address the regulatory control problems of the minerals processing industry. These will be discussed later. Effective stabilization control affords one the

opportunity to operate much closer to process limits, since the variation in the process is reduced. As a result, there is a much wider range for optimization control and more aggressive tonnages and recoveries can be chased.

### PlantStar control platform

During 2000 Mintek began in-house development on PlantStar, a generic, plant-wide control platform for the minerals processing industry. It serves as the new platform for Mintek's MillStar, Minstral and FloatStar control systems. It also allows for the combination of any number of control strategies on a single platform. This flexibility has enabled Mintek to investigate and easily develop new control strategies for both milling and flotation.

PlantStar is a PC-based control application that runs on the Windows 2000/XP platform. It can exchange data with almost any process by linking directly with the plant's DCS or PLC via the OPC communications standard.

### MillStar—advanced process control for grinding circuits

A milling circuit is a highly complex, multivariable interacting system. A milling circuit investigated by Hulbert and Lyon<sup>16</sup> was found to be an interactive multivariable system. Each plant output was significantly affected by more than one control action. There are several ways to deal with design of a control system for such plants. The technique used here was the design of a multivariable compensator by the use of the Inverse Nyquist Array (INA), which is based on the theory of Rosenbrock<sup>19</sup>.

Some work has been done on adaptive control of milling circuits. An ideal adaptive controller will be capable of controlling a process in some optimal fashion, irrespective of nonlinearities or physical changes in the process. An adaptive controller will never need to be tuned manually if the process dynamics change. Since almost all processes are nonlinear and their dynamics change with wear, changing environment conditions and changes in the input to the process, there is an immense scope for possible applications of an adaptive controller. The application of an adaptive controller in the metallurgical processes, and in particular the autogenous milling circuit, has been investigated (Metzner<sup>17</sup>). The adaptive control algorithm that was used here is the self-tuning placement controller of McDermot & Mellichamp<sup>18</sup>.

Modern milling circuits feature many of the controller types such as open-loop control, feedback control (PI and PID), as well as multivariable control. In the case of optimizing control, there are therefore several setpoints available for optimization. Craig *et al.*<sup>15</sup> applied optimizing control to a grinding circuit to optimize throughput based on mill power draw termed the 'Hill Climbing Technique.'

A study of the  $\mu$  methodology to a model derived from perturbation tests from a ROM (run of mine) milling circuit was investigated by Craig<sup>14</sup>. According to Craig<sup>14</sup> the  $\mu$  methodology will make it easier to design a control system for an industrial milling circuit because the dynamics of a ROM milling circuit contain large uncertainties due to the difference in size distribution and hardness of the feed ore. These uncertainties propagate themselves throughout the

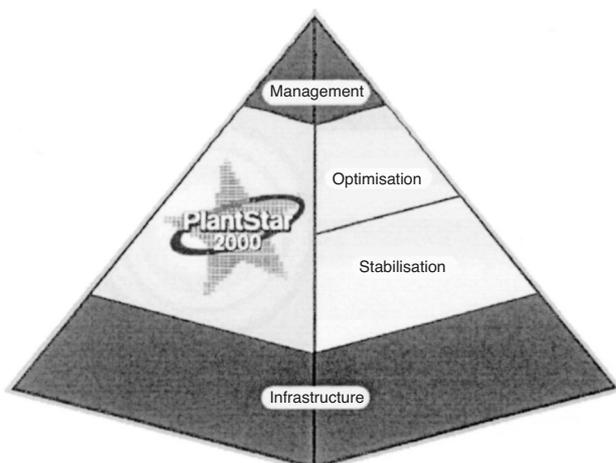


Figure 1—The process control hierarchy

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milling circuit and manifest themselves in plant parameter uncertainties (Craig<sup>14</sup>). The implementation of a controller on an industrial milling circuit requires considerable skill to achieve satisfactory performance of the controller. The  $\mu$  methodology provides a framework in which design decisions of an experienced control engineer can be structured.

Mintek's Measurement and Control division has been active in the field of milling control for more than 20 years. Over the years, vast experience and knowledge have been accumulated. As a result, a comprehensive suite of advanced process control tools, known as the MillStar suite, has been developed to address the specific control problems associated with grinding circuits.

The MillStar suite is packaged in the form of a plug-in module in PlantStar, Mintek's plant-wide, real-time process control engine. PlantStar is a flexible, powerful control platform capable of offering plant-wide control, from the crushers all the way through to the final product.

The MillStar suite has been implemented on a wide array of circuit configurations across the globe, including South Africa (PGM, Au), Zimbabwe (Ni), Botswana (Ni), Australia (Ni), Mexico (Ag/Pb/Zn), Brazil (Au/Cu) and Poland (Cu).

The first step in commissioning a MillStar is understanding the process. Before a control strategy is developed, Mintek engineers spend a considerable amount of time interviewing plant metallurgists, analysing data and auditing the process control infrastructure. With a good understanding of the process, an appropriate control strategy is developed together with plant personnel that addresses the specific process control problems and maximizes the performance of the circuit.

Efficient control of a milling circuit is essential for optimal circuit performance. An optimal milling circuit is one where throughput is maximized (without effecting grind), grind is stable, and all key operating variable (such as sump levels, cyclones densities, etc.) are within operating limits. Generally, the process indicators that determine how well the milling circuit is performing are:

- ▶ *The tonnes per hour milled*—the more tonnes milled during stable operation, the more product and revenue are generated
- ▶ *Stable product quality*—downstream processes, especially the flotation process, require a stable grind size, flow rate and density from the milling circuit for proper operation. A variable product quality will result in variable tailings and concentrate grades
- ▶ *Plant stoppages*—unscheduled plant downtime due to mill overloads, pump trips, etc. can be avoided by incorporating safety control loops that monitor the state of critical process units and take corrective action if process limits are violated.

MillStar has all the tools available to address these points and ensure that the process is performing efficiently.

### Common process control problems

Simple regulatory control of hopper levels, slurry densities, etc. are sometimes difficult to achieve due to inherent process characteristics and constraints. Some of these process constraints include:

- ▶ Large process dead times
- ▶ Few measurements and unreliable, noisy readings
- ▶ Few manipulated variables (actuators and variable speed drives)
- ▶ Constraints on inputs and outputs
- ▶ Multivariable interactive systems
- ▶ Nonlinear, changing system
- ▶ Many unmeasured disturbances.

Conventional control algorithms, as found on most DCS and PLC systems, do not really cater for these cases and have difficulty maintaining process stability.

### The MillStar suite of controllers

The MillStar suite includes many powerful controllers, designed to address the common problems associated with milling circuits.

### Mill Feed Controller

Large dead times are commonplace in the minerals processing industry, especially in milling circuits. A case in point is the typical ore feed arrangement to a mill. The point of measurement (weightometer) is far away from the control point (ore feeders). The dead time induced by the physical distance between the control and measurement points make controlling the solids feed to the mill very difficult. It is important to stabilize the feed to the mill, since a disturbance at this point is likely to affect the entire process. Standard PID controllers have to be detuned to maintain stability. As a result, there is sluggish setpoint tracking and poor disturbance rejection.

A *Mill Feed Controller* algorithm has been developed by Mintek. It includes a time delay compensation algorithm to accommodate for large dead times. This method makes use of advanced model-based techniques to compensate for the affects of the process dead time. The advantage of this algorithm above PID controllers and the classical Smith predictor algorithm is that it can quickly follow setpoint changes even with long dead times, but still remain stable and robust in disturbance rejection and handling model errors. These qualities are crucial in the minerals processing industry due to the many disturbances and model changes. Furthermore, the mill feed controller offers advanced ore feeder ratio control. This is important where stockpiles are segregated and the coarse: fine ratio to the mill can be controlled by the ratio between the ore feeders.

This algorithm has been used with huge success as can be seen from the results shown in the following two figures. Figure 2 shows the solids feed rate control using normal plant control. The PV is the measured solids feed rate, the SV is the setpoint and the MV is the % vibratory feeder speed in the feeder mechanism. From the graph it is clear that the normal plant control is sluggish; after a setpoint change it takes more than five minutes for the system to first reach setpoint and the control is slightly oscillatory.

When the time delay compensator is used (see Figure 3), the rise time is much quicker (in the order of 1 minute) and the response is not oscillatory, resulting in much quicker and better setpoint tracking. This will stabilize the grinding performance of the mill and will also aid in the better operation of downstream process units.

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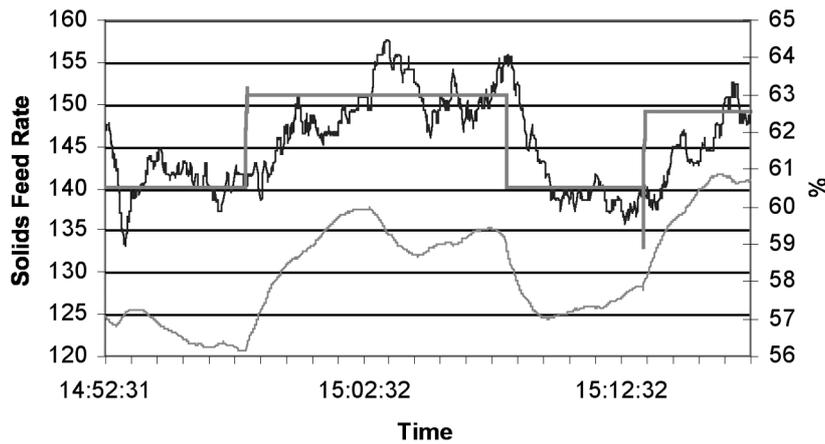


Figure 2—Solids feed control using normal plant control

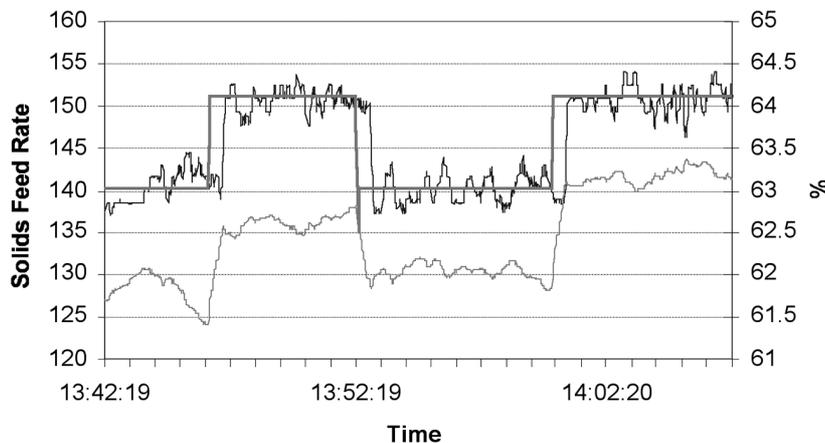


Figure 3—Solids feed control using delay compensator

### Safety limit selector

A common problem in milling circuits is that there are not usually enough manipulated variables to control all the required controlled variables to setpoint. As an example, consider the discharge end of a mill. The mill discharges into a hopper, where dilution water is added. From the hopper, slurry is pumped up to a cyclone classifier. Typical instrumentation includes:

- Flow rate and density measurements on the cyclone feed line
- Hopper level measurement
- Cyclone overflow particle size measurement.

We would like to control all these variables, if possible. We typically only have two control points (manipulated variables) that can be adjusted; these are:

- Hopper discharge pump speed
- Dilution water flow rate to the hopper.

Clearly this is not possible, since there are more controlled variables than manipulated variables. Some clever control algorithm is required to achieve control. Another complication is limit checking of all the measured variables; for example, the sump must not overflow or run dry and the density must not become too high or low. All this can be

accomplished by using limit-checking controllers. The problem with limit-checking controllers is that they often bump the plant when activating or deactivating. As a result, the plant often jumps or oscillates between safety control and normal control when one of the outputs is close to a limit. These problems have been overcome by developing an advanced switching algorithm that smoothly transfers the plant to safety control without bumping the plant. Once the plant returns to normal operation, the normal control strategy will smoothly take over control again. This strategy can also handle more than one restriction for every strategy and prioritize them such that the controller will give up control first for the limit with the lowest priority.

The problem with the shortage in manipulated variables is solved by not explicitly controlling non-critical outputs to be at setpoint all the time (e.g. the density). This variable is then allowed to drift between its limits and only once the limits are violated, will control for one of the other outputs be given up and control will smoothly switch over to this output. Once the output is back within the limits, normal control will resume. As a result, all measured variables are kept within specified limits and certain key variables are always controlled to an explicit setpoint.

Figure 4 illustrates the Safety Limit Selector in action. In this example, the sump level has violated its minimum

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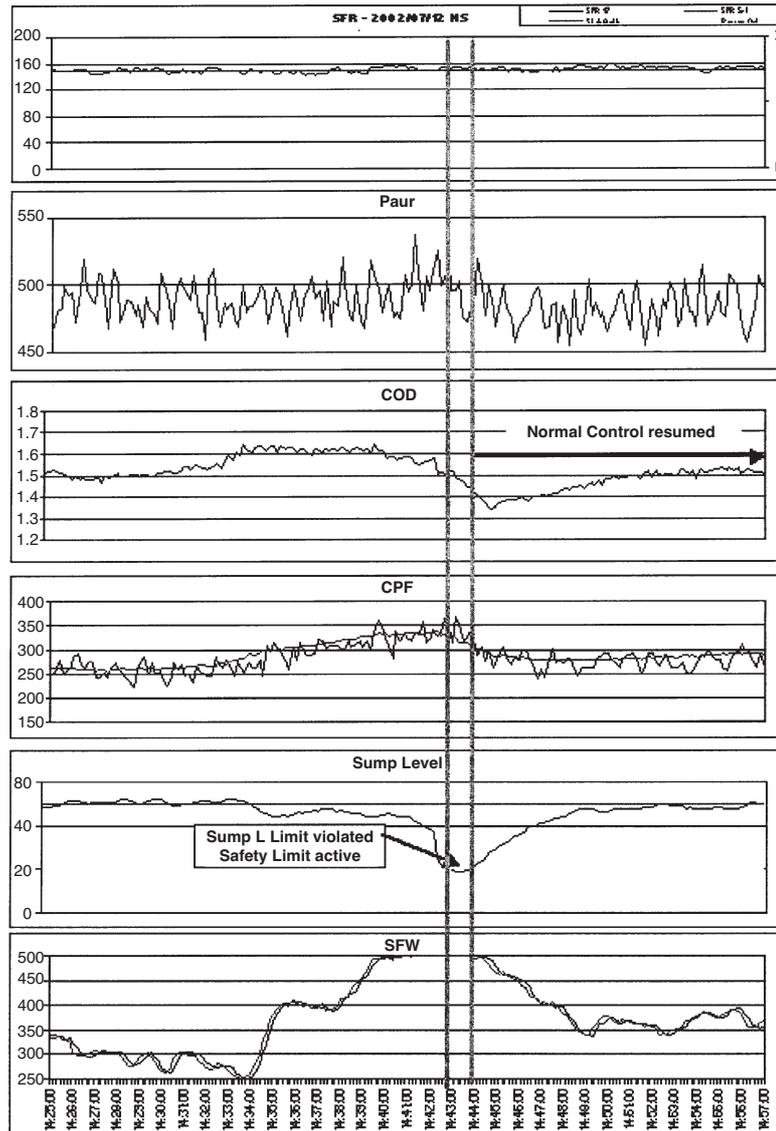


Figure 4—The safety limit selector restoring the sump level to normal operation

constraint. This was possibly due to a water supply problem. As a result, MillStar decreased the cyclone feed flow rate setpoint in order to retain more slurry in the sump. This was done at the expense of cyclone overflow density control. Once the sump was brought back under control, MillStar was once again able to control the cyclone overflow density to its setpoint value.

## The mill power peak seeking controller

It is often the case in grate discharge mills that there is a strong relationship between the mill load (or solids feed rate) and the power draw of the mill. The mill power is usually a parabolic function of the mill load, with a maximum power at a certain load value. As the solids feed rate is increased, the mill load will increase, causing the mill power to increase. The region of maximum power draw is often the ideal region of operation. If the mill load is increased further, there is a sudden drop in the mill power, due to a mill overload. This is a dangerous area of operation since mill overloads could

cause considerable downtime. This relationship is shown in Figure 5.

The objective of the mill power peak seeking controller is to dynamically find the zone of optimal grinding efficiency (i.e. the zone of peak power draw). The purpose of this non-linear controller would therefore be to use the solids feed rate to keep the mill operating at maximum power. What makes things more complicated is the fact that the whole parabola shown in Figure 4 can shift around as the feed conditions change. This means that the  $Load_{base}$  and  $Power_{max}$  are not fixed values. Furthermore, the mill power reading is very noisy, making it difficult to detect certain trends. To overcome these problems, a nonlinear controller has been developed that continually searches for the optimum power. This means that if the ore conditions change and the maximum shifts, the controller will follow the maximum.

The controller also has features built in, to bias it to operate at a slightly overloaded condition, as well as a safety controller that activates if the mill overloads and a sudden power dip occurs. This is illustrated in Figure 6. Once MillStar

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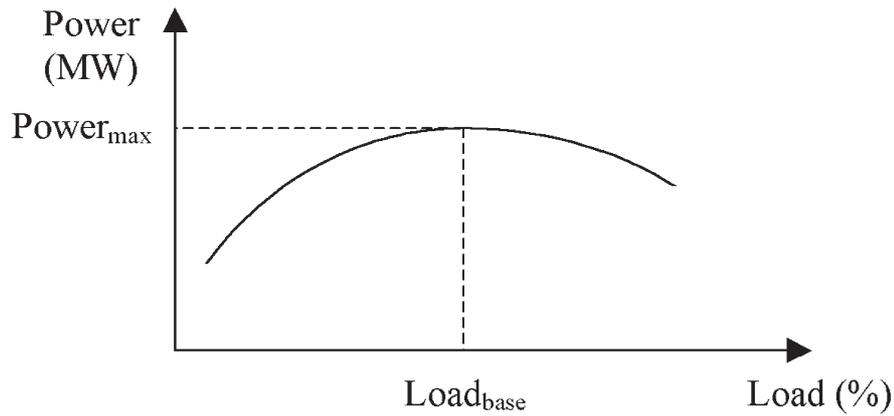


Figure 5—Power vs. load relationship in a mill

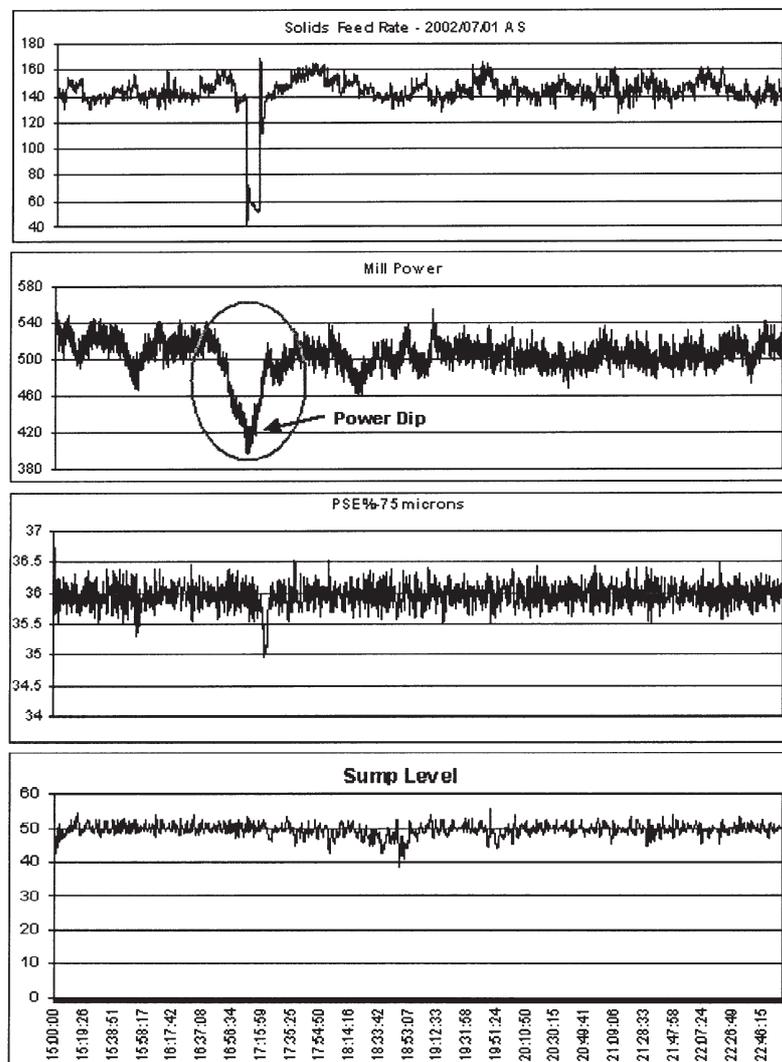


Figure 6—The mill power peak seeking algorithm detecting a power dip

detected a sudden dip in the power, it automatically cut the solids feed to the mill. In so doing, it gave the mill the chance to purge the overload and return to normal operating conditions.

With this facility in place, plants are able to run their

mills at consistently higher throughputs, knowing that MillStar is searching for the optimum throughput and will take corrective action if an overload is detected. Figure 7 shows how MillStar is able to consistently achieve higher throughputs, typically in the order of 5–10%.

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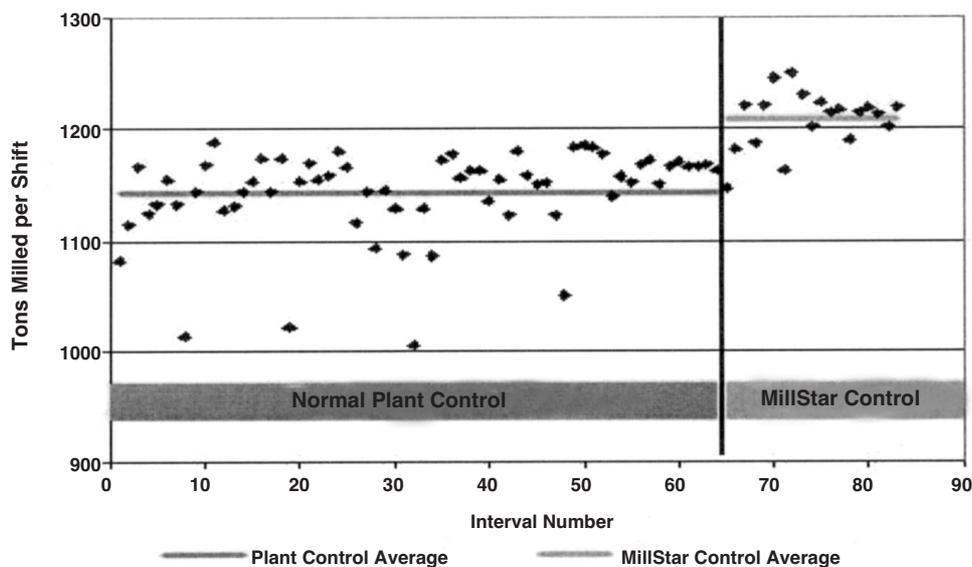


Figure 7—Increased throughput with the mill power peak seeking algorithm

### Other process control tools

Apart from the algorithms discussed above, numerous other stabilization and optimization control algorithms have been developed. Mintek follows the philosophy that each technique is used for addressing the problem it is most suited for. A common mistake is to use only one technique and exclude the others. Some of these are listed below:

- *Feed-forward controller*—compensates for the effects of measured disturbances on a process
- *Gain-scheduler*—developed for processes with varying process models, such as conical tanks, etc.
- *Advanced PID controller*—includes error-squared and higher order control
- *Fuzzy logic*—this rules-based controller has many applications in systems where process models are difficult to obtain
- *Model predictive control*—this model-based controller has application in systems where good process models can be identified. It is very good at dealing with multi-variable, interacting processes.

### Implementation of the MillStar

The control algorithms discussed are used together to build an overall control strategy that ensures optimal milling circuit performance. The overall control strategy can be roughly divided into two sections, advanced stabilization and optimization.

#### Stabilization

Stabilization of the milling circuit involves ensuring that all controlled variables track their setpoints and that no process limits are violated. Typical stabilization loops include controlling the solids feed rate to the mill, controlling all the sump levels, density control and particle size control. Sizeable performance benefits can be attained by stabilization control alone.

#### Optimization

Optimization strategies are implemented once the circuit is

operating stably. These strategies include increasing the solids feed through the mill by means of algorithms such as the mill power peak seeking controller and making use of intelligent logic to distribute loads between different process units.

### Flotation control—stabilization and optimization

It is possible to obtain good performance from a flotation plant, but it is often difficult to maintain such performance. Recovery rates on a flotation plant are typically around 90% on base metal plants and even as low as 60–70% on PGM plants. This makes flotation one of the least efficient processes in the mineral beneficiation cycle. As a result, over the last few decades much research and development has gone into the stabilization and optimization of flotation circuits.

Flotation is a process with many inputs and complex interactions. Manlapig and Franzidis<sup>7</sup> explain some of the current modelling techniques that account for the effects of 'true' flotation, entrainment and froth recovery. The modelling of flotation is reviewed by Mathe *et al.*<sup>6</sup> According to Edwards and Flintoff<sup>8</sup> the mathematical modelling and simulation of flotation systems have not evolved to the same extent as in comminution.

Technology for the control of flotation circuits has evolved somewhat independently from that of its modelling. McKee<sup>9</sup> describes three 'approaches' required for flotation control: stabilizing, setpoint and, finally, optimizing control. McKee<sup>10</sup> explains that simple proportional-integral controllers do not provide acceptable responses. Ding and Gustafsson<sup>11</sup> describe the application of a multivariable control strategy on an industrial flotation plant. A linearized model and a linear quadratic gaussian controller were used.

Van Deventer *et al.*<sup>12</sup> were of the opinion that neural networks have provided good scope for the analyses of froth characteristics as functions of their dynamically measured images. The advances in the use of froth imaging technology in process control are described by Brown *et al.*<sup>13</sup>

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Research into flotation control began in the late 80s when Mintek looked into the optimization of flotation circuits, particularly grade and recovery. These tests involved xanthate addition and its effect on grade and recovery. The results from this test work indicated that it was not possible to obtain a reasonable model between xanthate addition and recovery or grade. A closer look at the froth depth data during this period indicated that the froth levels in the flotation cells were oscillating. Hence it was concluded that it was not feasible to measure and model the effect of xanthate on grade or recovery while there are oscillations in level (Singh *et al.*<sup>5</sup>), since these oscillations themselves influenced the grade and recovery. For that reason the initial focus was placed on developing a good level control system rather than optimizing a circuit that was not stabilized.

Process control and optimization have a direct influence on the efficiency of flotation plants. An inefficient operation can cause an incorrect balance between grade and recoveries and can also lead to adverse shifts in the grade-recovery relationship. Flotation loses the largest proportion of valuable material when compared to other metallurgical processes. These losses can be reduced by improved operation of the flotation process (Singh *et al.*<sup>5</sup>).

Optimal or efficient performance of a flotation circuit can be achieved when the circuit is well stabilized in terms of flotation levels and optimized in terms of circulating flows (i.e. optimized level and aeration setpoints) and reagent consumption to obtain a desired grade and recovery.

## Flotation stabilization—FloatStar level stabilizer

Improved flotation operation can be achieved by improved stabilization, regulation and optimization of the flotation circuit (Singh *et al.*<sup>5</sup>). Once stable operation is achieved, the true performance of the plant is observed, without being obscured by the effects of disturbances and fluctuations. Only then should optimization strategies be considered.

The control of flotation plants can be achieved by controlling aeration rate, reagent addition or froth depth. However, these control actions are effective over different time scales. Reagent addition is slower in its effect as some conditioning time is required. Also, since reagents are typically introduced at the head of the circuit and at intermediate points within the banks, it requires time before they start having an effect on flotation performance. Reagent addition, due to its long response time, will therefore be a more effective control action for an optimizing strategy.

Aeration rates and froth depths have a quick and immediate response on the performance of flotation. They are able to react within a few seconds and make adjustments quickly to counter any deviations or disturbances caused by flow variations. However, on most plants aeration rates are not available for automatic control because many conventional cells are self aspirating and airflow can only be manipulated by manual adjustment of the valves. This then leaves froth depth, or its equivalent pulp level, as the most generally used variable for stabilization of short-term disturbances on flotation plants. Other requirements for stabilizing control would be level measurements and automatic control valves.

Levels in flotation cells are conventionally controlled by PI (proportional and integral) control loops. PI control will

work well when the cell being controlled is isolated. However, flotation cells are connected in a network, and the tailings stream from one cell is likely to be fed to another cell. Similarly, the concentrate flows will generally be fed into banks higher up in the circuit. This results in strong interactions between levels in a flotation circuit. Thus, if a change in control action is made at any point in the circuit, this would result in the disturbances being propagated to both upstream and downstream units.

To counter this problem, Mintek has developed and implemented a level controller called the FloatStar (Schubert *et al.*<sup>1</sup>) level stabilizer. The controller monitors all the levels in the circuit and acts on all the control valves, taking the interactions of levels into account. The advantage is that the control valves on banks further downstream in the circuit can be opened as soon as the disturbances enter the respective banks. The FloatStar level stabilizer has been implemented on several flotation circuits worldwide, some applications of which are described by Henning *et al.*<sup>2</sup>, Singh and Schubert<sup>3</sup>, and Muller *et al.*<sup>4</sup>

## FloatStar level stabilizing control—industrial application

The application of the FloatStar level stabilizer will be illustrated by means of a case study. The part of the flotation circuit chosen is the primary rougher section. All the banks are in series. That is, the tails of the upstream banks forms the feed to the downstream bank. This part of the circuit is very interactive due to the connectivity of the tailings stream.

A graphical comparison for conventional PID control versus FloatStar control is shown in Figure 8. The first 9.5 hours show the circuit under conventional PID control and thereafter under FloatStar control.

From Figure 8 it can be seen that levels under FloatStar level stabilizing control outperform conventional PID control. The control on primary rougher 1 and 2 is satisfactory under PID control. However, minor oscillations begin in primary rougher 3 and these oscillations propagate all the way through to primary rougher 9. It is also evident from Figure 8 that the disturbance not only propagates downstream but also amplifies as it moves downstream.

With FloatStar control, the circuit stabilized and remained at setpoint for the rest of the testing period. Control disturbances are dealt with more effectively by FloatStar level stabilizing control than with PID control. There is no propagation of disturbances with FloatStar control from bank to bank. The results indicate that the FloatStar level stabilizing controller is robust enough to reject many disturbances completely. With PID control these disturbances are passed to downstream banks with magnification.

The data in Figure 8 was analysed for the standard deviation of the error (difference of level setpoint and measured level). The statistical analysis of the levels for all the data analysed is given in Table I. The closer the standard deviation of the error is to zero, the closer the level is to setpoint.

Table I shows a statistical summary of the data analysed for the primary rougher circuit. The standard deviation of the error (Setpoint - Level) for all the levels is smaller with FloatStar control. The per cent improvement column confirms

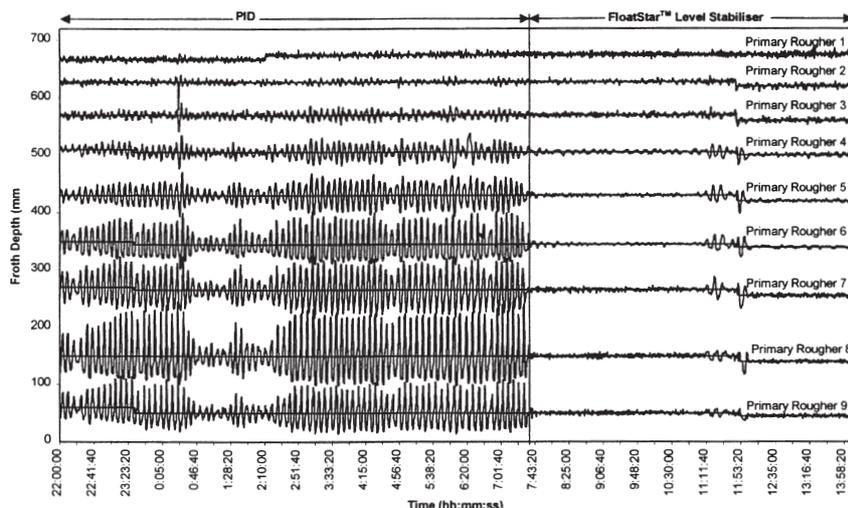


Figure 8—Comparison between PID and FloatStar control for the primary rougher circuit

Table I  
**Statistical summary of the primary rougher circuit level control**

Standard deviation of the error—0primary roughers			
	PID control	FloatStar control	% Improvement
Primary Rougher 1	2.95	2.86	3.33
Primary Rougher 2	3.58	2.80	21.63
Primary Rougher 3	5.57	2.86	48.65
Primary Rougher 4	9.87	3.60	63.56
Primary Rougher 5	16.08	3.62	77.52
Primary Rougher 6	23.41	3.75	83.97
Primary Rougher 7	25.58	4.16	83.74
Primary Rougher 8	35.78	3.62	89.88
Primary Rougher 9	21.94	2.59	88.17

the improvement in level control, with the improvement varying between 3.33% and 89%. The data in Table I shows that the improvement in level control when FloatStar is on control is significant. Note the % improvement (all over 20% except for primary rougher 1). This is because of the connection of levels via tailings streams in the circuit. With conventional PID control, disturbances gets passed to downstream banks. Hence levels tend to oscillate frequently in the cleaner circuit.

### Flotation optimization—FloatStar flow optimizer

The first task in optimizing the process is to decide exactly what targets need to be set. The overall objective is to maximize economic returns, but it can take some thought to formulate how this is best achieved. Incorrectly set targets can be misleading. For example, two commonly used plant objectives are to:

- maintain the concentrate grade at a pre-defined level, and
- maximize the recovery.

If an unsupervised optimization algorithm were set loose with these objectives, it would reduce the throughput if it

could, as this will lead to higher recoveries. The detailed objectives will vary from process to process and will depend on metal prices, transportation costs, refining costs and contractual stipulations (Singh *et al.*,5).

There are many variables to look at when trying to optimize a flotation circuit. These include mass pull, reagent concentrations, air flow rates and level setpoints. With enough process measurements and control elements, a circuit can easily be optimized because there are many degrees of freedom.

Most flotation circuits, however, have limited instrumentation, with only level, valve actuators and occasionally aeration rates for each bank. This leaves basic level control as the only real control in place. With this limitation, flotation operators attempt flotation optimization by changing level setpoints and sometimes aeration rates' setpoints to increase or decrease concentrate mass flow rates. However, is the choice of these setpoints correct? If the choice of these setpoints results in the mass balance and the flows being properly controlled at optimum values, then the answer is YES. However, more often than not the answer is NO.

With good level control in place, the effects of adjusting level and aeration setpoints can generally be seen in the product quality. Mintek has found that controlling residence times and circulating flows in the circuit can optimize the product quality. Controlling residence times and circulating flows is not a trivial problem. Factors that affect concentrate pull off cells (and hence circulating loads) include pulp level setpoints, aeration rates and reagent addition. The challenge is to combine all these inputs to control the circulating loads, since there are more manipulated variables than controlled variables. The system is over specified, but this can be used very effectively in a multivariable controller to increase the ranges of control. The controller developed by Mintek to accomplish this is called the FloatStar flow optimizer. This controller ensures that the maximum controllable range and quickest responses are obtained by using all the available manipulated variables to control the circulating flows. Since this control is at the optimization level, the control is slower than stabilization control.

# Innovative process control technology for milling and flotation circuit operations

With residence times and mass pulls optimized throughout the circuit, there should be a significant improvement in the performance of the flotation circuit. Also with the mass balance and flow properly controlled, reagent addition can be adjusted to achieve the final product quality.

## FloatStar flow optimizing control—industrial application

The FloatStar flow optimizer has been installed on commercial flotation circuits. Data has been collected and some of the results are presented in the following example.

This part of the circuit consists of 9 primary roughers, 7 secondary roughers and 6 cleaners as shown by Figure 9 below.

The Flow optimizer was configured to:

- Control the flow into cleaner 6 to setpoint by changing the level and aeration rate setpoints of primary roughers 1–4 and secondary roughers 1–3 as well as the level setpoints of cleaner 1–5

- Control the flow into cleaner 1 to setpoint by changing the level and aeration rate setpoints of primary roughers 5–9 and secondary roughers 4–7.

Since there is no measurement of flow into the cleaners, this flow was inferred by a special estimating filter based on available plant measurements. With the inferred measurement of flow and a supplied setpoint for this flow, the optimizing algorithm was able to adjust the level and aeration rate setpoints of the roughers.

Data was collected over a 24-hour period in order to assess the flow optimizing controller. Figures 10 and 11 illustrate the level and aeration control for primary roughers 1–4, secondary rougher 1–3 and cleaners 1–5. The data shown is for operation with PID control first, followed by the floatStar level stabilizer and then the flow optimizer. It should be noted that the individual curves have been shifted up or down to make them all visible, but the magnitude of the variation has not been changed.

It can be seen that levels under FloatStar level stabilizing control outperform conventional PID control. With FloatStar

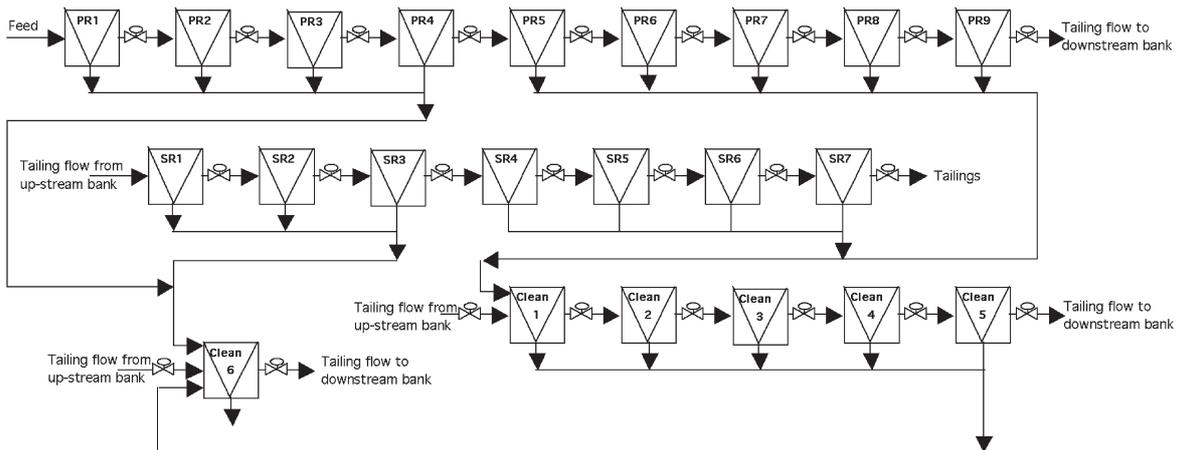


Figure 9—Circuit for flow optimizer example

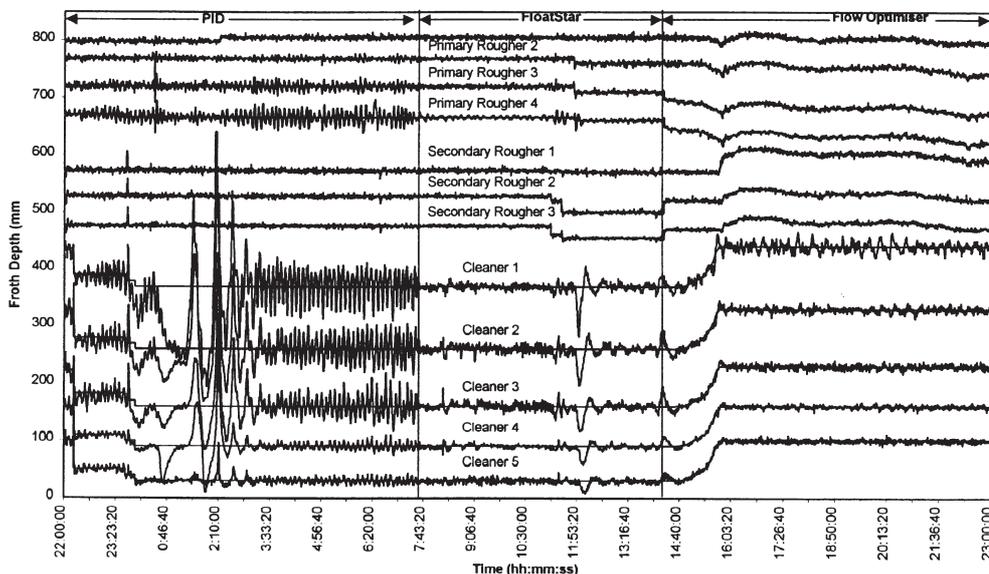


Figure 10—Level setpoint tracking for control of flow to cleaner 6

# Innovative process control technology for milling and flotation circuit operations

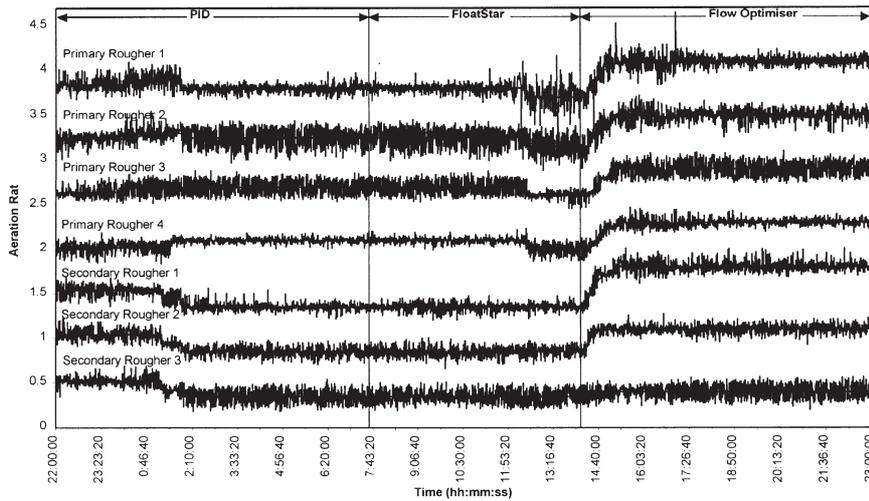


Figure 11—Aeration Setpoint tracking for control of flow to cleaner 6

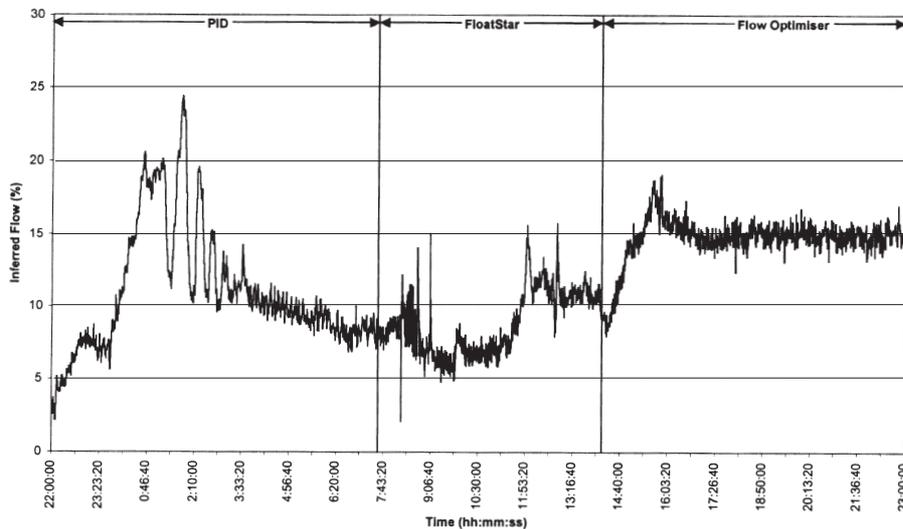


Figure 12—Control of flow out of cleaner 6

control disturbances are dealt with more effectively than with PID control. There is no propagation of disturbances with FloatStar level stabilizing control from bank to bank. The results indicate that the controller is robust enough to reject many disturbances completely. With PID control these disturbances are passed to downstream banks with magnification.

When the flow optimizer was switched on, the level and aeration rate setpoints changed gradually in order to produce the required inferred flow of 15% through the cleaner. Setpoint tracking on both the level and aeration rate are satisfactory. Figure 12 shows the inferred flow from the cleaner over the 24-hour period. It can be seen that there's virtually no control of the flow under normal PID control, and therefore uncontrolled flows throughout the circuit. When the flow optimizer control is switched on, the concentrate flow from primary roughers 1-4, secondary roughers 1-3 and cleaners 1-5 was varied to control the flow from cleaner 6 around 15%.

The data was analysed statistically in order to compare the working of the different controllers. The results obtained

are presented in Table II below. The analysis was done in terms of the standard deviation of the error. The error was representative of the difference between the flow setpoint and the actual flow.

From the data in Table II it can be seen that there's basically no control over the flow through the cleaner under PID control. The deviation of the error is significantly less under FloatStar level control, and when the flow controller is switched on, the error is further minimized.

	Standard deviation of error
PID	4.2
FloatStar level stabilizer	2.20
FloatStar flow optimizer	1.44

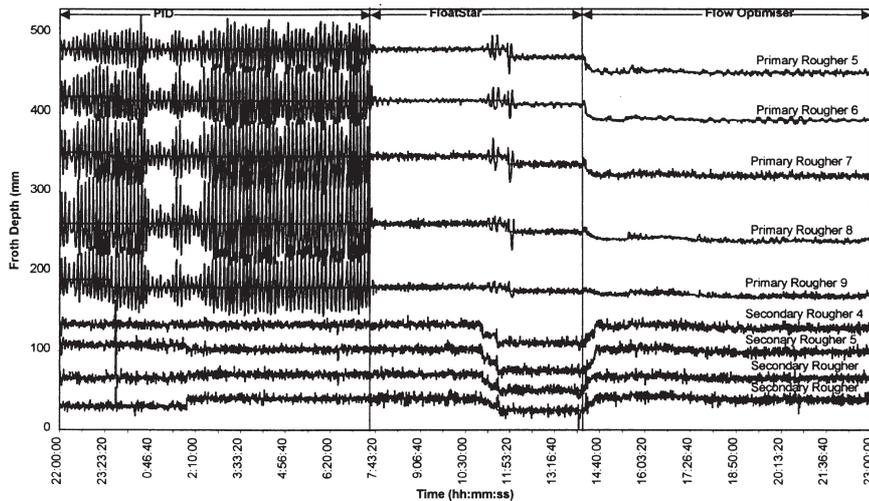


Figure 13—Level setpoint tracking for cleaner 1 control

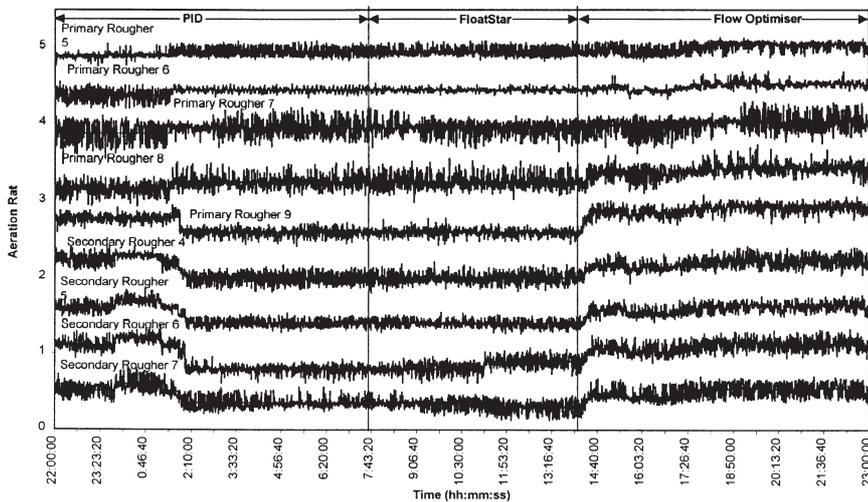


Figure 14—Aeration setpoint tracking for cleaner 1 control

Figures 13 and 14 show the results obtained for the level and aeration control on primary roughers 5–9 and secondary roughers 4–7. The data shown is for operation with PID control first, followed by FloatStar level stabilizer and then the flow optimizer.

Once again it can be seen that control disturbances are dealt with more effectively with FloatStar level stabilizer than with PID control. When the flow optimizer was switched on, the level and aeration rate setpoints changed gradually in order to produce the required flow of 15% (inferred from the estimating filter) through cleaner 1. This is shown in Figure 15.

From the statistical analysis provided in Table III, it can once again be seen that the flow optimizer managed to minimize the standard deviation of the error and control the flow closer to the flow setpoint. The error was representative of the difference between the flow setpoint and the actual flow.

### Other process control tools

Apart from the stabilization and optimization algorithms

discussed above, Mintek has developed numerous other control algorithms for control of flotation circuits. An example of these is the FloatStar grade-recovery optimizer.

Optimizing grade and recovery can be coupled with dynamic optimization of circulating flows in a flotation circuit. The FloatStar grade-recovery optimizer is a software algorithm incorporated into PlantStar that maximizes grade in a section, whilst ensuring that recovery or any other process-specific limits remain within predefined limits.

It provides a higher level of control than that provided by FloatStar level controller. It calculates optimal level setpoints and/or aeration rates of the cells that contribute concentrate flow to a specific section, to ensure that the section is operated in an optimal fashion regarding grade, recovery and operational constraints. The level setpoints are provided to the FloatStar level stabilizing controller, which stabilizes the levels at the required setpoints.

The algorithm is highly configurable, allowing the user to add any number of safety limits to the control strategy. It will ensure that none of the safety limits is violated during the optimization process. It furthermore incorporates data-

# Innovative process control technology for milling and flotation circuit operations

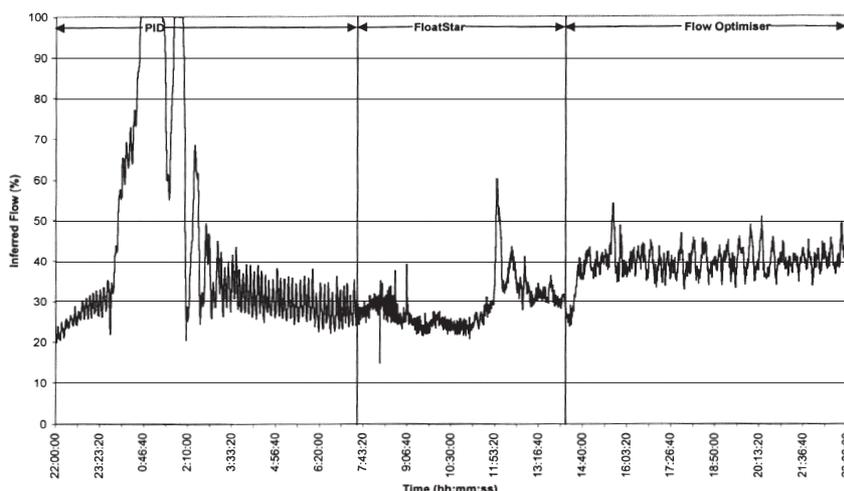


Figure 15—Control of flow out of cleaner 1

Table III

### Statistical analysis for the flow into cleaner 1 circulating flow

	Standard deviation of error
PID	24.56
FloatStar level stabilizer	5.92
FloatStar flow optimizer	3.60

validation functionality, ensuring data integrity and ensuring that control is not compromised as a result of unreliable measurements.

## Conclusions

It has been illustrated that Mintek has a complete suite of tools available on the PlantStar platform to effectively stabilize and optimize both milling and flotation plants.

The MillStar increases both recovery and throughput by making use of a range of tools to stabilize and optimize milling circuits.

Data has been presented on the performance of the FloatStar level stabilizer and the resulting improvements in level control on the plant.

The FloatStar flow optimizer provides a new tool for optimizing concentrate flow in the flotation circuit, thereby providing a technique for controlling residence time in various sections of the plant.

The grade controller takes the flow optimizer one step further, and controls the product quality directly by manipulating some combination of pulp level, aeration rate and reagent addition. The controller is designed to prioritize recovery while attempting to ensure a consistent product.

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The following members have been admitted to the Institute as Company Affiliates.

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AEL	Durban Metro	Ninham Shand (Pty) Ltd
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