CIM ICM

Technical Paper

Mineral Processing

Optimum control of the Leeudoorn semi-autogenous milling circuit

W. van Dyk, W. Stange, Hatch Africa (Pty) Ltd., Johannesburg, South Africa
J. Derbyshire, Northam Platinum Limited, Gold Fields of South Africa Limited, and
H. Williams, Kloof Gold Mining Company, Leeudoorn Division, Gold Fields of South Africa Limited

KEYWORDS: Automation, Fuzzy logic, Grind-ACE, Grinding circuits, Leeudoorn Gold Mine, Mineral processing, South African mining.

Paper reviewed and approved for publication by the Canadian Mineral Processors Division of CIM.

ABSTRACT

Intelligent control techniques, such as fuzzy logic, have been successfully applied to the control of a semi-autogenous (SAG) grinding circuit at the Leeudoorn Gold Mine. Benchmarking showed that circuit performance was enhanced by the control system. Benefits included a significantly more stable circuit, improved power efficiency, a reduction in the amount of steel grinding media required, as well as more consistent throughput. A software system, Grind-ACE, based on the intelligent autonomous agent-blackboard paradigm, was developed as an implementation platform. This approach has proved successful and flexible, allowing both intelligent and traditional control techniques to be integrated. The control system has been implemented in a unique manner with both stabilizing and optimizing capabilities, which has resulted in a flexible and adaptable system.

Introduction

There are a number of advantages associated with semi- or fully-autogenous (SAG/FAG) grinding, such as lower capital and operating costs, as well as easier operation due to reduced circuit complexity. However, SAG/FAG circuits do have some disadvantages, such as their sensitivity to feed conditions, i.e. changes in size distribution and mineralogy/"hardness." Feed variations result in product variations (throughput and product size distribution) that may adversely affect downstream recovery processes, such as leaching and flotation. These variations may lead to significant losses in revenue over the operating life of a grinding plant.

When compared to the more robust two-stage SAG, ball mill circuit traditionally used in other parts of the world, the typical South African practice of single-stage SAG milling is particularly sensitive to feed conditions. Therefore, a significant incentive to develop appropriate and effective automatic control strategies for SAG/FAG grinding circuits exists. Possible benefits associated with such control strategies would be:

- Operating costs associated with grinding often represent a significant proportion of overall processing cost. An automatic control system provides opportunities to save on both power and media costs.
- Variation in product size from the grinding circuit may influence downstream recovery processes in a detrimental manner. Reducing such variations may result in significant recovery improvements.
- Improvements in throughput may result in an increase in revenue, assuming that increased throughput does not result in significant losses in recovery in other sections of the plant.

Grinding Circuit Control

The objective of an automatic control system is site dependent. Objectives are typically stabilization of circuit operation, improved consistency of operation, maximization of throughput as well as the stabilization of the product size distribution. In this work an attempt was made not only to meet such objectives, but to do this in a manner which results in optimum economic performance.

The automatic control of a SAG/FAG circuit is difficult as the process is non-linear, multi-variable and non-stationary (short and longer term). Measurements are difficult to make, may be noisy, and significant effort needs to be put into maintaining instruments effectively.

Despite these difficulties many reports in the literature (Herbst and Lo, 1994; Borell et al., 1994; Meriluoto and Jarvensivu, 1994; Hulbert et al., 1990) demonstrate that mill control can be successfully achieved using a variety of technical approaches (model-based, multivariable and rule-based). Therefore, selecting an appropriate route from the various competing approaches should be judged by business-oriented criteria such as:

- time and cost taken to develop and implement the system;
- ease of use of the system for plant operators and technical staff;
- ease with which the system can be modified to incorporate changing circuit conditions. Ideally, the system should be adaptive to ensure that changes in operating conditions are dealt with without the requirement for controller re-calibration or modification.
- system flexibility in terms of the manner in which the system can be evolved to incorporate other factors, not necessarily included during the original controller design, e.g. the automatic control of steel addition for a SAG mill;
- ease of maintenance of the system — The system should be designed in a manner which minimizes maintenance requirements so that the system can be easily adapted to new circumstances.
- technological adaptability — Computer-based control systems evolve very rapidly at present. What may be state-of-the-art today, could be redundant in three years. A mill control system contains a significant amount of knowledge and is the result of significant effort. It should, therefore, be relatively easy to adapt the system to technological changes in the underlying plant control system. At present, plant automa-

tion is dominated by Microsoft™ technology with Windows NT™ making significant inroads. This trend could be expected to continue for some time. The mill control system should, thus, be compatible with this technology base.

- mainstream technology — If the mill control system is not based on mainstream technology (i.e., Microsoft Windows®) it will not integrate into the plant control and information system effectively, making it much more difficult to obtain information and to transfer this into the plant information system.
- support — There will always be a need for technical and operational support for a mill control system, to ensure that the system continues to operate in the most effective manner possible. Close contact with plant staff is required to allow identification of potential control system problems which could be caused by planned plant modifications, as well as to identify further opportunities for improved plant control.

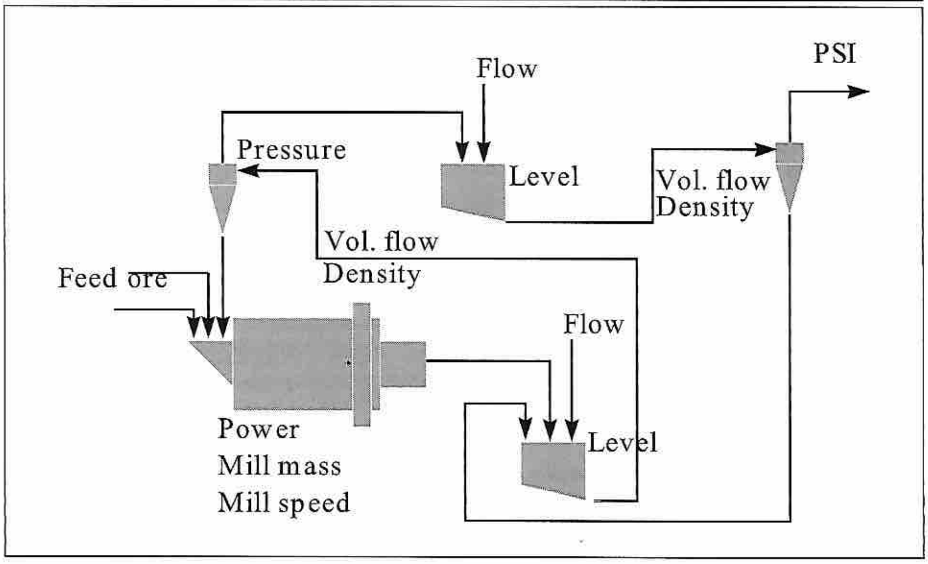
The Leeudoorn Grinding Circuit

Production at Leeudoorn commenced around December 1991 (Williams et al., 1996). Throughput is currently around 120 000 tons per month, through two Polysius 5 m by 11 m single-stage SAG mills, each equipped with Siemens variable speed gearless ring motor drives. Classification is achieved by two-stage hydrocyclones, with a final product size of 80% passing 75μm (Fig. 1). The grinding circuit is well instrumented (Fig. 1) and is followed by conventional thickening, cyanide leaching and carbon-in-pulp (CIP) circuits.

The plant control system consists of a number of Siemens 150H PLCs (distributed according to functional plant area) connected to a Wonderware InTouch supervisory control system via a Siemens H1 bus.

Figure 2 and Figure 3 show typical operating data (30 second averages) acquired on the circuit before the commissioning of the mill control system. Large variations in circuit performance can be seen clearly, particularly in the final product size distribution. Of particular interest is the effect of feed chute chokes on circuit performance. Figure 3 shows how a mill choke leads to a rapid fall in mill mass, with consequent effects on operational efficiency. Due to the highly non-linear nature of the relationship between mill load and feed flow rate, the operators find it difficult to keep the mill mass in a narrow operational band. Due to the relatively fast dynamics associated with cyclone performance, operators have little chance of keeping the final product size distribution reasonably constant.

Fig. 1. Leeudoorn grinding circuit.



A Hybrid Control Framework: Grind-ACE

Intelligent Control System Architecture

MacLeod and his research group (Lun and MacLeod, 1991, 1992; MacLeod and Stothert, 1994) have developed a framework for distributed real-time intelligent computing. This approach provides for multi-agent, multi-paradigm, distributed intelligent controllers and is acknowledged to be appropriate for the control of large, complex systems, such as plant-wide intelligent control. The agent-based paradigm for intelligent control appears to be gaining rapid popularity due to the relative ease with which complex control systems can be developed. The approach of multiple disparate, intelligent agents, interacting in order to solve a complex problem, is a key concept currently being broadly exploited by the computing fraternity.

In this approach, the problem is decomposed into tasks where each task is solved by an intelligent agent. The core elements making up an agent-based approach are a blackboard, agents and algorithms. The blackboard is a repository for data, and allows data items required by various agents to be easily accessed. Data items are identified by a structure tagging convention. Each agent can be considered as an executable 'sub-program' and encapsulates the logic required to fulfil its particular task and is executed at the frequency required by the natural dynamics of its control task. This may be once every few seconds for fast control (e.g. particle size control), once every few minutes (e.g. mill load control), or once every few hours (e.g. economic optimization).

Each agent may use one or more of the standard algorithms available in the algorithm library. High level complex algorithms such as fuzzy logic and neural network algorithms exist, as well as lower-level algorithms such as filtering and averaging are also available as required.

The agent-based approach was adopted as a basis for the mill control system, as it was judged to be sufficiently flexible to support all of the potential control technologies that would be required. For example, this approach could easily support the development of a control strategy that mixes intelligent algorithms such as fuzzy logic and classic control techniques, such as MVC.

An appropriate agent-based software system, Grind-ACE (Advanced Control Engine for Grinding Control), based on the model presented by Lun and MacLeod (1991, 1992), was developed and operates under Windows 95™ and NT™. This system has operated on-line at Leeudoorn since October 1995, has proved to be robust and flexible as well as computationally efficient and has been able to operate effectively on low-end computer hardware.

Grind-ACE is interfaced to the plant control system via the Siemens H1 PLC network allowing Grind-ACE to read information from the PLCs, as well as to write setpoint changes to the local controllers in the PLCs via Wonderware InTouch™. This architecture also allows Grind-ACE to control other parts of the plant as it is able to access the other PLCs on the plant control network. The InTouch supervisory system is used as a man-machine interface for the mill control system.

Development of the Mill Control System

From the initiation of the project, much attention was paid to defining the objectives that the mill control system should meet. It was ultimately found that four categories of control are required:

Fig. 2. Product size (before mill control).

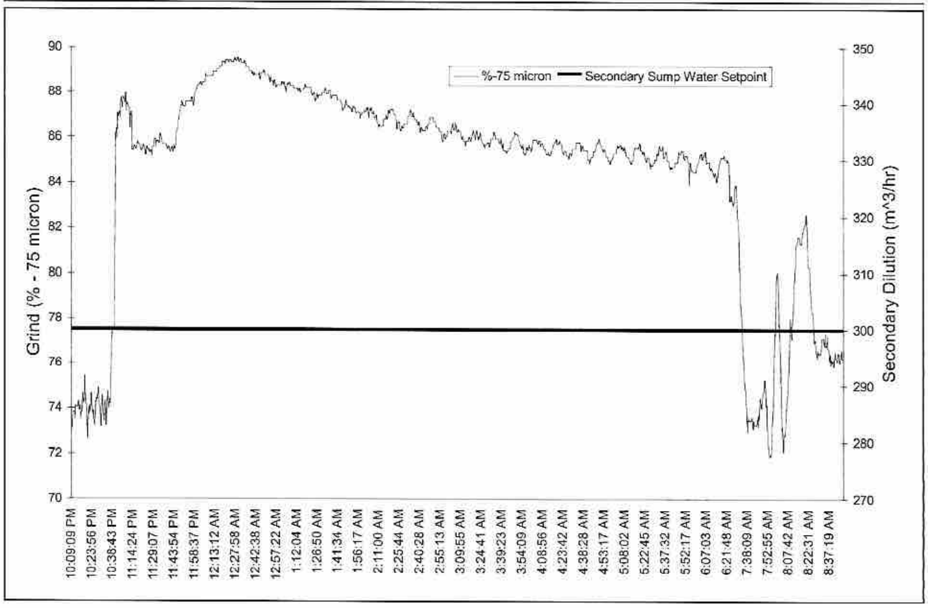


Fig. 3. Load and feedrate (before control).

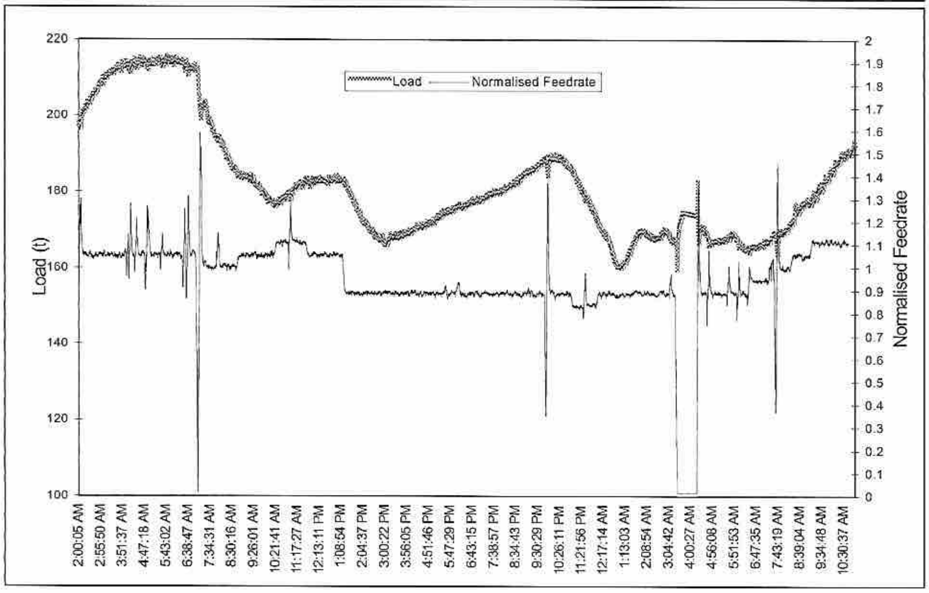
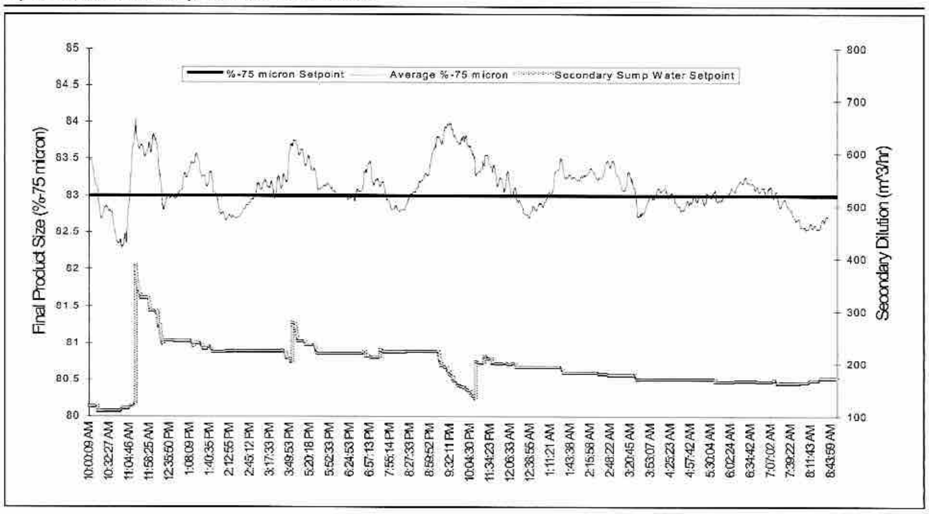


Fig. 4. Control of circuit product size distribution.



1. Stabilizing Control — operate the circuit at a pre-set mill load while producing the specified product size distribution.
2. Primary/Secondary Cyclone Interaction — regulate the interaction between the primary and secondary cyclones to ensure that the circuit parameters are such that the specified circuit product size distribution can be attained.
3. Mill Load Optimizer — manipulate the mill load setpoint to drive throughput to the required value.
4. Operating Cost Optimizer — use additional manipulated variables, such as mill speed and the rate of steel addition to ensure that the circuit operates in the most cost-effective manner.

The stabilizing control algorithms were implemented, tested and fine-tuned before embarking on the development of the optimization algorithms.

Development of Stabilizing Control

The agent-based approach requires that the overall control system problem be decomposed into a number of sub-tasks, each of which can be solved or controlled by a particular agent. After spending a significant amount of time observing the dynamic behaviour of the plant, as well as studying the response of the plant to various manipulated variables, the following decomposition was developed:

- Mill Load Control Agent — Uses a fuzzy logic controller to control the mill load at a specified setpoint by manipulating the feed rate. It was found that rate of change information (i.e., rate of change of mill load, rate of change of feed rate) was important to incorporate into the agent in order to obtain effective control.
- Primary Cyclone Agent — Uses a fuzzy logic controller to control the primary cyclone feed pulp density at a specified setpoint by manipulation of dilution water, thus stabilizing the circulating load. Although it should have been possible, in principle, to implement this control as a PID loop, the non-linear interactions due to two-stage classification made this impossible to achieve.
- Secondary Cyclone Agent — Final product size distribution is controlled by manipulation of secondary cyclone dilution water by a fuzzy logic controller.

Other agents were also required and implemented. For example, a supervisory agent ensures that realistic setpoints are entered, coordinates changes to data and so on. There are several other agents in the system used to perform various computational tasks (such as filtering, moving averages, rates of change, differences, and so on), as well as general tasks such as logging status reports to disk and reading and writing data to and from the PLCs.

Fuzzy Logic

Although there is claimed to be a deep philosophical basis for this technology (Kosko, 1994), a more pragmatic view was taken for this project. Fuzzy logic is merely seen to be an appropriate manner in which to represent knowledge about the manner in which a grinding circuit can be controlled and is essentially a rules-based approach. It has an implicit advantage over the use of more traditional Knowledge Based Systems (KBS) approach, in that:

- Fuzzy rules are a more natural and less complex means of expressing the dynamic relationships between controlled and manipulated variables in a grinding circuit.
- The approach also deals with contradiction in a more pragmatic manner.
- Significantly fewer rules than those which would be required in a KBS with similar capability are typically required.
- Rule execution is more deterministic from a real-time computing perspective, making it easier to use mainstream computing technology, rather than a sophisticated real-time operating system, as the implementation platform.
- The fuzzy rules also allow the multi-variable nature of the grinding system to be dealt with explicitly by structuring the rules in an appropriate manner.

The fuzzy rules developed in this project were based on a generic understanding of the grinding circuit behaviour that had been developed by:

- the use of a detailed dynamic simulation of the circuit to develop deeper insight into circuit dynamics;
- the observation of plant behaviour by studying dynamic plant data, as well as by spending time on the plant and observing the operation of the circuit; and
- knowledge gained about grinding circuit performance acquired through several grinding circuit audit and modelling studies.

Development of Optimization Agents

Once the circuit had been stabilized, agents were designed to optimize performance as follows:

- Primary / Secondary Cyclone Interaction — An agent was designed to manipulate the primary cyclone feed density setpoint to ensure that the secondary cyclone was achieving the required product size distribution.
- Throughput Optimization — A fuzzy logic controller was designed to ensure that the average throughput required on a longer term (shift, daily) was achieved. This agent manipulates the mill load setpoint at a frequency of about 30 minutes in response to the difference between the actual throughput obtained over the 30-minute period and that required.
- Operating Cost Optimization — Lowest cost circuit performance can be achieved by manipulating the mill speed and rate of steel addition to respond to changing ore characteristics. The power and steel media cost of producing a unit of product is calculated by the optimizer which then uses a minimization routine to manipulate mill speed and steel addition rate to keep operating costs as low as possible.

Control System Performance

Figure 4 and Figure 5 show the tight control achieved with stabilizing control active. Figure 6 shows how the primary cyclone density setpoint is manipulated in order to achieve tight control in the secondary cyclone classification control block.

Williams et al. (1996) have published a summary of the benefits associated with the implementation of Grind-ACE, based on the extensive validation of Grind-ACE performed after commissioning. These results are illus-

Fig. 5. Control of mill load.

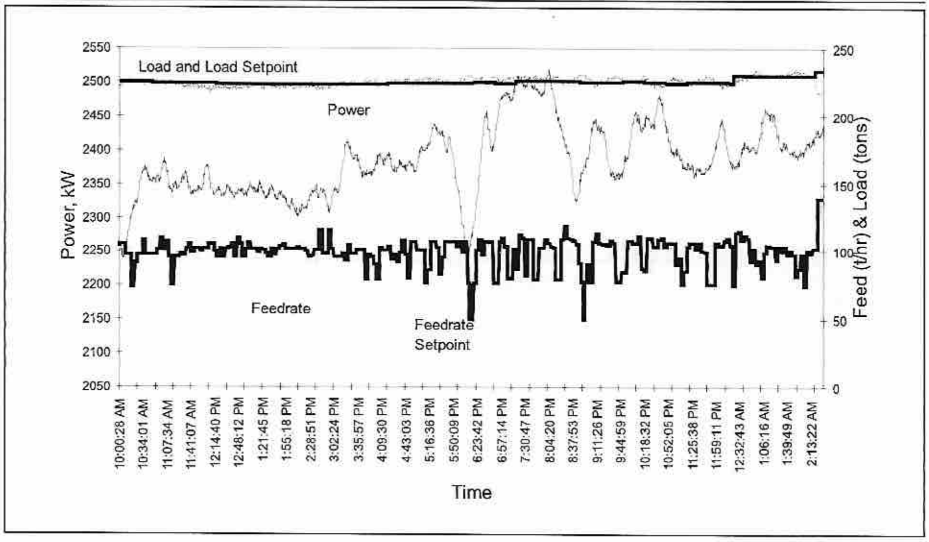


Fig. 6. Primary / secondary cyclone interaction.

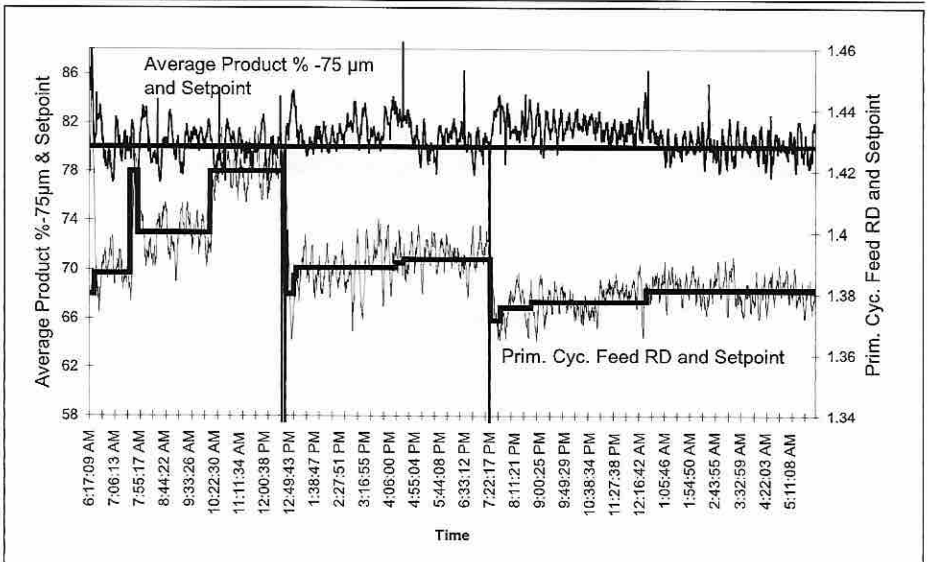


TABLE 1. Comparison between circuit performance with and without mill control

Control mode	Throughput t/hr	Grind %-75µm	Grind std. dev.	Mill load tons	Mill load std. dev.	Power kW	Efficiency kWhr/ton -75µm
Manual	88.2	83.7	1.76	205	20.5	2 660	36.0
Grind-ACE	97.7	83.0	0.52	211	2.3	2 638	32.5

trated in Table 1. It was also found that the addition rate of grinding media could be decreased by some 15%, from 0.88 kg/ton to 0.75 kg/ton. These improvements translate into significant economic benefits.

Conclusions

The use of intelligent control techniques, such as fuzzy logic, for the control of SAG/FAG grinding circuits has been investigated at the Leeudoorn Gold Mine. It was found that this approach results in a robust, reliable and adaptable control system which has improved the performance of the grinding circuit significantly. A unique feature of the approach is that an economic optimization capability has been incorporated into the control system, such that the circuit is optimized economically while being controlled in a stable manner.

During this project, a hybrid control platform, Grind-ACE, has been developed as an implementation platform for intelligent control systems. This system is not restricted to SAG/FAG grinding control and it is envisaged that it can be effectively applied to many other process systems.

References

BORELL, M., BACKSTROM, P. and SODERBERG, L., 1994. Supervisory control of autogenous grinding circuits. 8th European Symposium on Comminution, ICRA, Stockholm, May.

HECHT-NIELSEN, R. 1990. Neurocomputing. Addison-Wesley Publishing Company.

HERBST, J.A. and LO, Y.C. 1994. Financial implications of comminution systems optimization. 8th European Symposium on Comminution, ICRA, Stockholm, May.

HULBERT, D.G, CRAIG, I.K., COETZEEE, M.L., and TUDOR, D., 1990. Multivariable control of a run-of-mine milling circuit. Journal of SAIMM, Vol 90, No. 7, p. 173-182.

KOSKO, B. 1994. Fuzzy Thinking, Flamingo.

LUN, V. and MACLEOD, I.M., 1991. A test-bed for distributed real-time intelligent computing. South African Journal of Science, Vol. 87, July.

LUN, V. and MACLEOD, I.M., 1992. Strategies for real-time dialogue and interaction in multiagent systems. I.E.E.E. Transactions on Systems, Man and Cybernetics, Vol. 22, No. 4. July/August.

MACLEOD, I.M. and STOTHERT, A.M., 1994. A simulation study of distributed intelligent control for a deep shaft mine winder. IFAC Artificial Intelligence in Real-Time Control, Spain.

MERILUOTO, T. and JARVENSIVU, M., 1994. On-line stabilisation expert in grinding control. 8th European Symposium on Comminution, ICRA, Stockholm, May.

WILLIAMS, H., CUNNINGHAM, G.I., DERBYSHIRE, J.R., and GOSSMAN, G.I., 1996. Leeudoorn Gold Mine's Approach to SAG Milling. SAG 1996, Vancouver.

NEWS IN BRIEF

CFI FUNDS CERM3

Dr. David Strangway, CEO of the Canadian Foundation for Innovation (CFI), has announced approval of funding for the Centre for Environmental Research in Minerals, Metals and Materials at The University of British Columbia. Out of 30 submissions to CFI, UBC received support for 19 projects totalling 41 million dollars. Together with the CFI award for the BC Cancer Research Centre ($28 million), UBC received the highest CFI support of any university or institution in Canada. Of the 363 million dollars in this round of awards, 20% of the total funding was allocated to British Columbian institutions.

CFI's contribution to CERM3 is 1.25 million dollars which is matched by support funding from the British Columbia Knowledge Development Fund and an internal university grant from the Stewart Blusson Endowment Fund. The total funding available to launch the CERM3 initiative is 3.4 million dollars which will be used to create five interdisciplinary research laboratories to work on environmental problems in the mining industry. It is indeed fitting that a portion of the generous gift made by Dr. Blusson to UBC ($50 million) be used to address fundamental problems associated with mining and the environment.

The on-going research will be sponsored by Canadian mining companies through corporate membership in CERM3 with matching funds derived from both levels of government — Canada and British Columbia. For information about corporate membership, contact Dr. John A. Meech at: jam@mining.ubc.ca, or by phone at (604) 822-3984.

CERM3 will be housed in the department of Mining and Mineral Process Engineering at UBC. The MMPE department was recently selected by The Princeton Review's Gourman Report as the top mining engineering program in Canada and number two in North America. Led by Dr. Malcolm Scoble, the department has taken on the visionary role to lead the mining industry into the 21st century in the area of **sustainable mining** — a concept which places equal importance on environmental, social-political, economic, and technical issues. CERM3 will develop solutions to a number of environmental problems faced by the mining industry. Over 25 faculty members and 50 graduate students and post-doctoral scientists from 10 UBC departments will work together in CERM3 to find innovative solutions for environmental problems in mining and related industries.

Dr. John A. Meech has been appointed as the first director of CERM3.

The five research facilities that make up CERM3 include: Environmental Quality Lab, Bioremediation and Reclamation Lab, Environmental Technology Lab, Mine Health and Safety Lab, and Mine Automation and Environmental Simulation Lab.

The Canada Foundation for Innovation (CFI) is an independent corporation established in 1997 by the Canadian federal government to strengthen Canadian capacity for research. Its mandate is to increase the ability of Canadian universities, colleges, hospitals, and other not-for-profit institutions to carry out world-class scientific research and technology development. The CFI promotes innovation by investing in research infrastructure, jointly with institutions and their funding partners. The CFI has been entrusted with an investment budget of $1.9 billion directed at research in health, the environment, science, and engineering. The Foundation contributes 40% of the eligible project costs. On this basis, total investment funding by the Foundation and its partners will exceed $5.5 billion by 2001. In February 2000, the federal government extended the mandate of the CFI to 2005.