INSTRUMENTATION AND PROCESS CONTROL

W. E. Horst, associate director—mineral processing, and **R. C. Enochs,** research metallurgist, Amax Extractive Research & Development Inc., Golden, Colo.

Applications of instrumentation and process control continue to gain ground at modern mineral processing operations—the need for such advanced technology being dictated by lower-grade raw materials, larger scale of operations, and more complex processing facilities. With increasing energy requirements per unit of metal production, brought on by diminishing ore grade and higher energy costs, the utilization of additional instrumentation and advanced process control is vital to achieve competitive operating costs at newly built, capital-intensive plants.

Over the past two decades, numerous existing plants have been modified to incorporate instrumentation and process control systems. While the actual implementation of this type of equipment may be more costly in the older plants, having multiple parallel circuits of smaller capacity, successful installations can be cited. At the Morenci operations, N. Mex., of Phelps Dodge Corp.[1], grinding-circuit control resulted in a 2.5% increase in throughput when applied to 30 parallel grinding circuits processing about 2,000 stpd per circuit. Similarly, a 4.4% increase in throughput was achieved at the Climax operations, Colo., of the Climax Molybdenum Co.[2,3] when grinding-circuit control was implemented on 20 parallel grinding circuits handling from 1,800 to 4,200 stpd per circuit, depending on the ball mill size.

Providing and maintaining instrumentation for these multiple-circuit installations is more expensive than providing and maintaining such instrumentation for fewer high-capacity parallel circuits found in new plants, yet significant financial benefits have still been achieved at older installations. At both new and existing mineral processing operations, increased productivity, process stability, improved recovery, reduced operating costs, or a combination of these benefits have provided the financial justification for increased use of instrumentation and process control.

Recent advances in instrumentation and process control hardware have made it easier to implement and maintain process control systems. A wide array of sensors is available to measure the major process variables at mineral processing operations. Advances in process control hardware, including system architecture, have simplified installation and maintenance requirements, as well as providing a more cost-effective system. In some instances, overall system cost has actually been reduced.

This article discusses the status of current instrumentation and process control technology as applied to major unit operations in the mineral industry, including crushing, grinding, classification, flotation, thickening, filtration, and drying. Flowsheets for typical instrumentation schemes are included. While the coverage is intended to include both domestic and international developments, omissions may well have been made, and the article may not be all-inclusive. Selected industrial applications are reviewed, and numerous references to other applications are cited.

PRIMARY CRUSHING

In the true sense of "process control." such controls usually

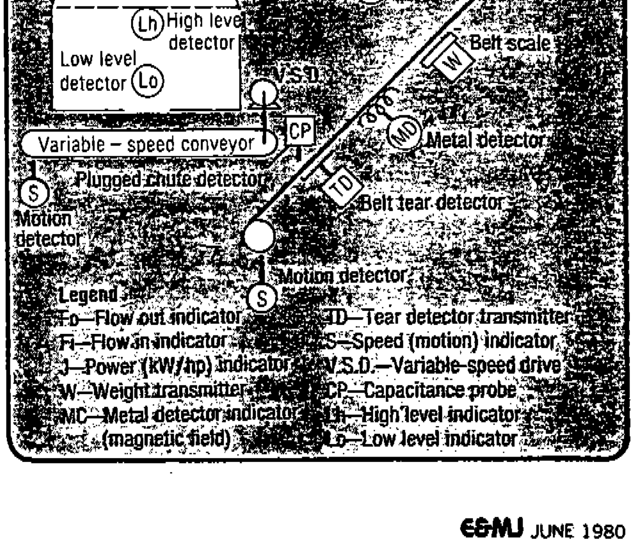
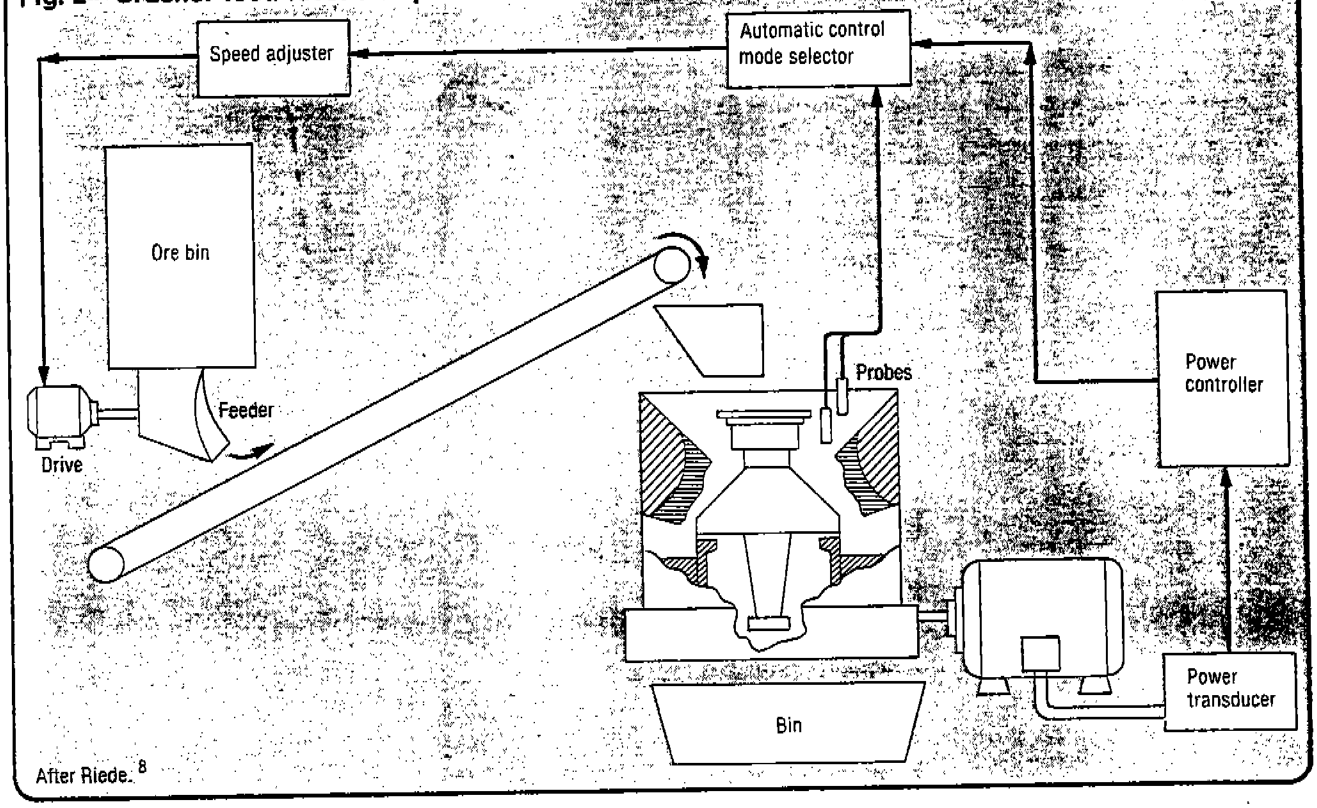


Fig. 1—Basic instrumentation for primary crushers

Fig. 2—Crusher feed level and power control



are not applied to primary crushers. However, basic protective instrumentation is common. Normally, a crusher is protected against loss of lubrication through the use of lubrication-flow indicators and/or bearing-temperature detectors, with an alarm followed by timed shutdown in the event of loss of lubricant flow or high bearing temperature.

Both high- and low-ore levels are usually monitored in the chamber under the crusher: the high level to protect the crusher from ore buildup or packing under the crusher, which would stop it, and the low level to protect the crusher discharge conveying system from being hit by large pieces of ore. Either a closed-circuit video system or nuclear level detectors can be used to monitor both high and low levels. Sonic level detectors are also in use, and tilt switches are used to monitor low levels in particular.

A motion detection device attached to either the driven shaft or an idling shaft normally monitors the crusher discharge conveying system. The speed of travel of the system is manipulated to maintain the ore level in the chamber between the high and low level marks, and it can be limited by a conveyor-weighing device to prevent overloading of upstream conveyors. To protect the crusher motor from overloading, crusher power frequently is monitored and alarmed at some high point. This monitor will indicate either current or kilowatts to measure horsepower. (Fig. 1 illustrates a typical primary crusher with basic instrumentation for protecting the crusher and upstream equipment.)

2° AND 3° CRUSHING

The operating and process control objectives for secondary and tertiary crushing plants differ from one plant to the next; however, such objectives usually include one of the following[6]: to maximize throughput at a constant product size, to maximize throughput while producing a product finer than some upper limit, or to produce as fine a product as possible at a constant throughput. Usually, the objective[7] is to maximize crusher throughput at some specified product size.

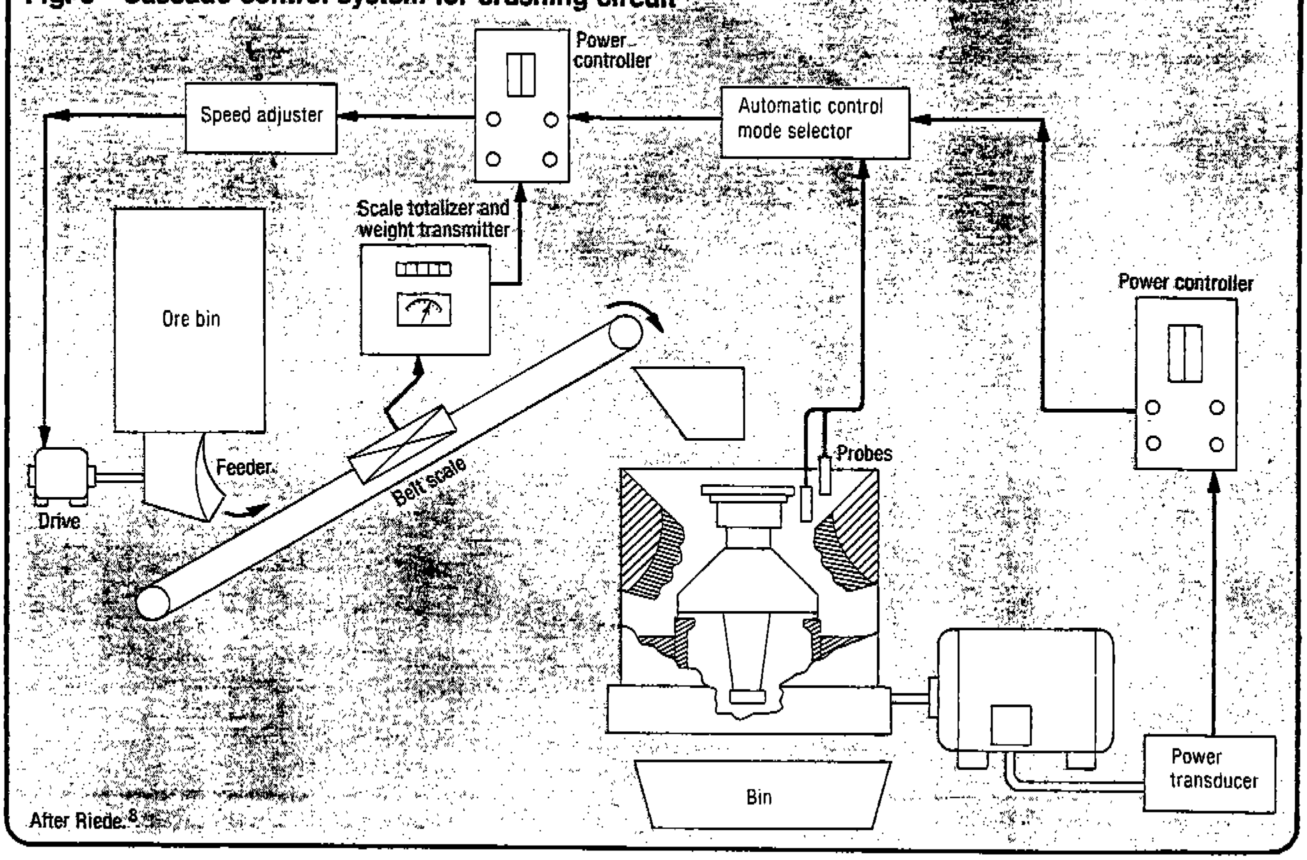
In some plants, both secondary and tertiary crushers are instrumented and controlled, while in others, only the tertiary crushers are controlled. In all cases, lubrication flow to the crushers is monitored and alarmed for crusher protection, as at primary crushers.

Riede[8] notes that a clear and well-defined statement of the control objective is a must if control is to succeed, adding that "In most instances, this objective becomes the automatic maintenance of maximum throughput within the defined constraints." He lists the following constraints for a single-stage crushing installation (constraints that are also applicable to multiple-stage crushing): the size of the crushed product must be within specified limits, the feed must not be increased to where it will plug the crusher, and the control must never induce a condition where physical damage to the crusher or any related component will result.

In normal day-to-day operations, numerous variables affect the performance of a crusher; however, only three—ore feed rate, crusher opening, and in some instances, feed size—can be adjusted. The crusher opening, depending on the crusher design, can be controlled either continuously, as on the Allis-Chalmers hydrocone crusher, or intermittantly by mechanical means, as on Symons-Nordberg or Telsmith crushers.

An effective crusher control system that uses automatic feed control to maintain a condition of choke feed, subject to countermanding by the onset of limiting input horsepower, is illustrated in Fig. 2. The system controls feed rate by monitoring the high-level and low-level probe signals in the crusher bowl. At high level, the feed rate is decreased, and at low level, it is increased. If both probes are uncovered and the power draw is maximum, the feed rate is decreased. This control system is applicable to either single- or multiple-

Fig. 3—Cascade control system for crushing circuit



crushing units, with each crushing unit having its own control system.

A cascade control system with feed rate control maintained by feedback from the belt scale is illustrated in Fig. 3.

A crushing-plant control system developed and in use at Mount Isa Mines Ltd., in Australia, has been described by Lynch.[9] The computer-based system was developed using a crushing system model and simulation studies. The flowsheet and instrument diagram for the secondary and tertiary crushing plant are illustrated in Fig. 4. The surge bins receive ore from the primary and secondary crushers, respectively.

INSTRUMENTS FOR CRUSHERS

Instrumentation employed in crushing circuits, some of which has been mentioned already, include ore level detectors, oil flow sensors, power measurement devices, conveyor belt scales, metal detectors, motion detectors, variable-speed conveyor drives, variable-speed feeders, and plugged-chute detectors. A partial list of manufacturers and suppliers of crushing circuit instrumentation is found in Table 1. The list is intended to indicate general availability of various sensors and is not complete. There are many suppliers. Several manufacturers, including Ramsey Engineering Co. and Milltronics Inc., provide crushing control systems designed for specific crushing plant applications.

GRINDING AND CLASSIFICATION

Because the two functions are usually interdependent, grinding and classification may be considered as one process in terms of instrumentation and control. Grinding can be accomplished by a number of methods, both wet and dry. Here, only single-stage or multi-stage wet-grinding circuits that incorporate autogenous mills, semiautogenous mills, rod mills, ball mills, or pebble mills will be considered.

In implementing instrumentation and process control for grinding circuits, the following features must be considered: definition of the objective to be achieved by grinding control, definition of the controllable variables in the grinding circuit, available sensors that may be used to detect changes in the grinding circuit operation, and techniques for controlling the process variables to compensate for disturbances in the grinding circuit operation. Potential control objectives could be as follows: 1) maintain a constant grind size at maximum throughput, 2) maintain a constant feed rate within a limited range of grind size, and 3) maximize productivity per unit time in conjunction with downstream circuit performance (i.e., flotation circuit recovery).

When changes in ore grindability occur, either because of changing ore hardness or feed size distribution, the product particle size, the feed rate, or both must be moderated, and adjustments must be made to the process. In adjusting feed rate upward, care must be taken not to overload the circuit. Hence, there exists an upper limit to the ore feed rate.

Usually, there are economic constraints on the product particle size. Particles that are too large or too small can result in an economic loss. For example, recovery of valuable metals, which is a function of liberation and mineral separation characteristics, may be reduced in subsequent unit operations.

The following measurements can be accomplished in grinding circuits: ore feed rate, water feed rate (individual sources and total), mill power draw, mill bearing pressure, mill sound, classifier feed rate, classifier feed density, and classifier product particle size (measured or inferred). Of these variables, only the ore feed rate and water feed rate can

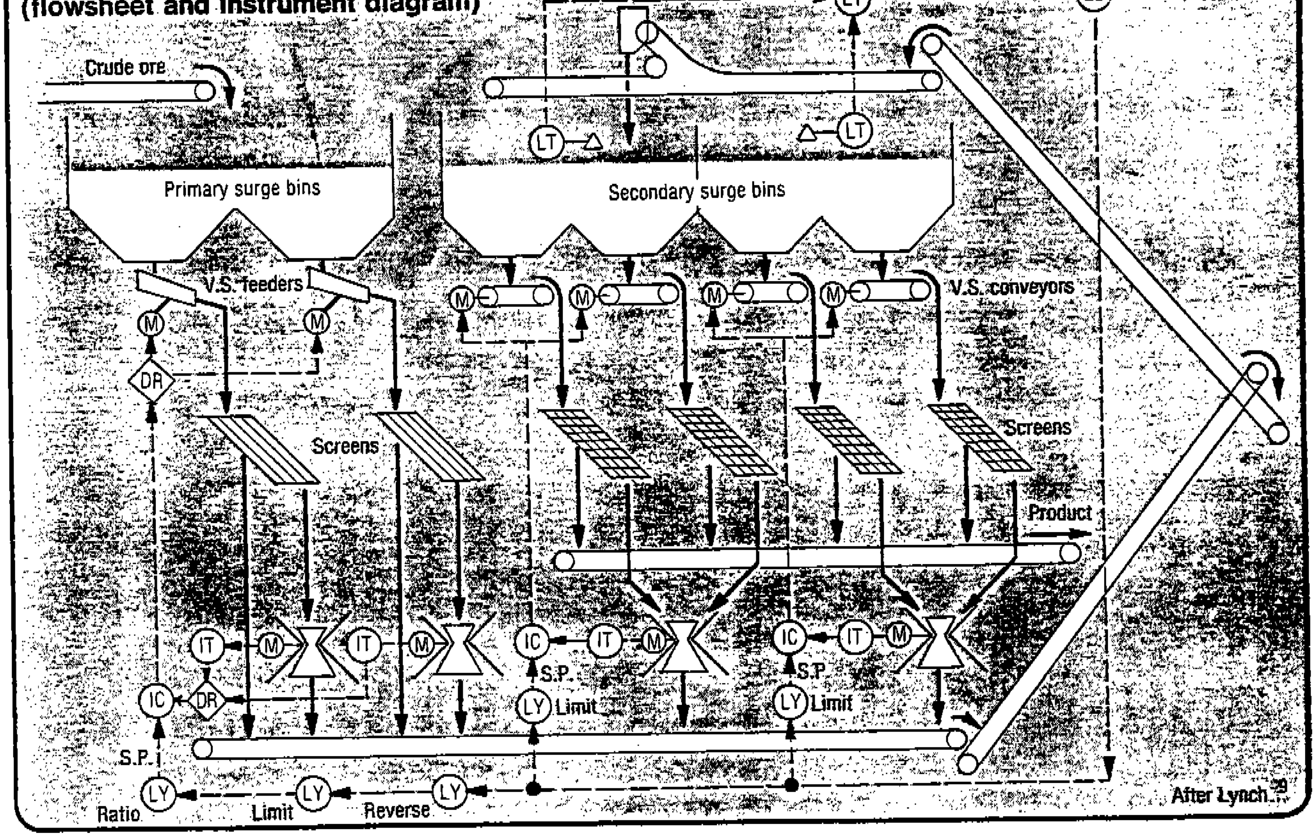


Fig. 4—Lead-zinc crushing plant, Mt. Isa Mines Ltd. (flowsheet and instrument diagram)

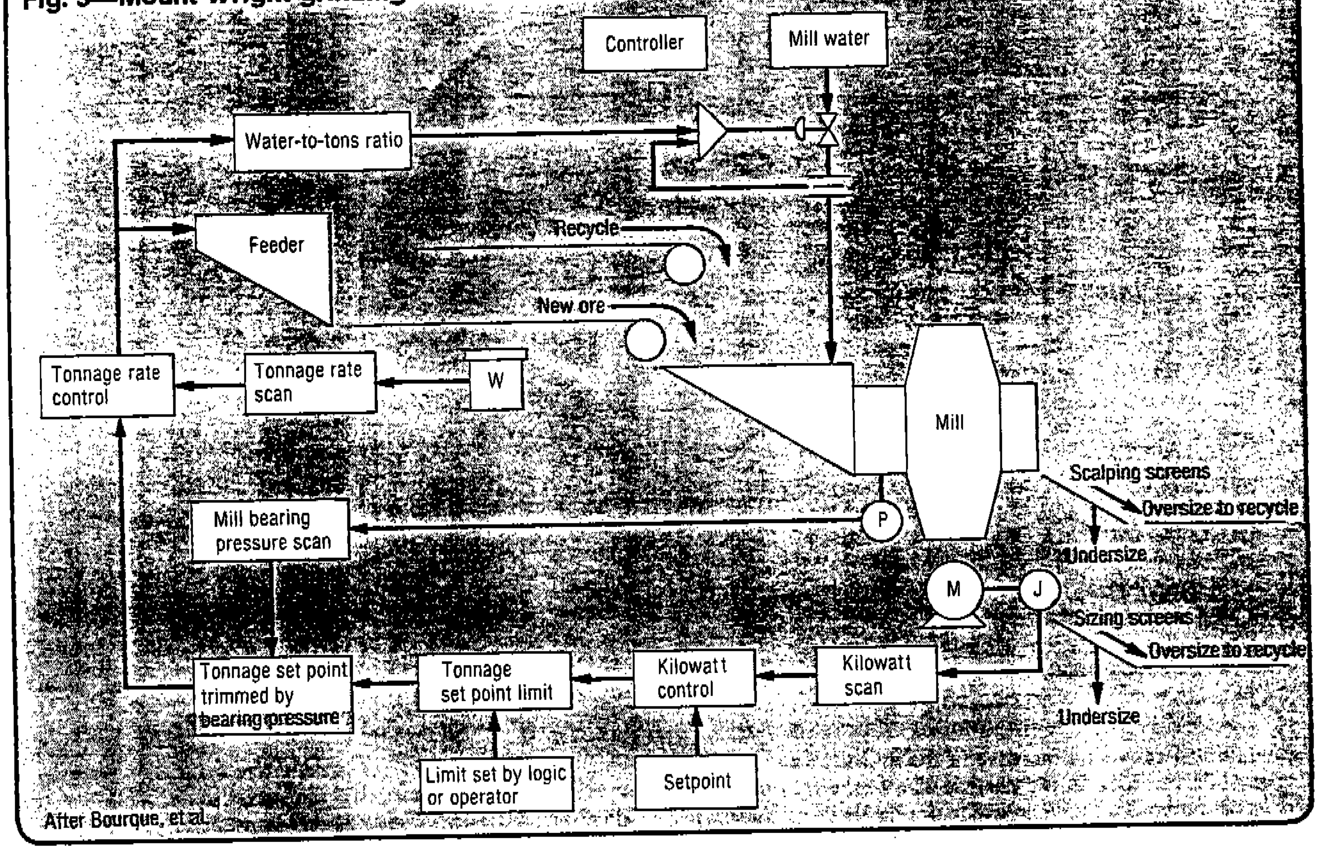
be varied independently. Because the other variables depend upon and respond to changes in the ore and water feed rates, control of the grinding circuit is achieved by manipulating ore and water feed rates. Introduction of a variable-speed pump for use in hydrocyclone classification would introduce another degree of freedom in control strategy.

In this review, control will be discussed for the following types of grinding circuits: single-stage autogenous mill, semi-

Table 1—Manufacturers and suppliers of crushing circuit instrumentation

Instrumentation	Manufacturers and suppliers	
Ore level detectors Sonic type	Endress & Hauser Inc. Milltronics Inc. National Sonics Div., Envirotech Corp.	Rexnord Inc. Wesmar Industrial Systems
Closed circuit video systems	Hitachi Motorola Xedar	RCA Corp. Westinghouse Electric
Nuclear (gamma ray)	Kay-Ray Inc. The Ohmart Corp.	Texas Nuclear Div., Ramsey
Tilt switches	Conveyor Components Co. Milltronics Inc.	Ramsey Engr. Co.
Lubrication oil flow sensors	Brooks Instruments Ernst Gage Co. Fischer & Porter Co. The Foxboro Co.	GEMS Sensors Square D Company Universal Flow Monitors Wallace and Tiernan
Power measurement and transducers	Crompton Instruments Milltronics Inc. Ramsey Engr. Co. Nastec Inc.	Rochester Instrument Systems Valeron Corp. Westinghouse Electric
Conveyor belt scales	Fairbanks Morse Div., Colt Industries Howe Richardson Kay-Ray Inc Belt Weighing Systems	Merrick Scale Mfg. Co. The Ohmart Corp. Ramsey Engr. Co. Texas Nuclear Div., Ramsey
Metal detectors and tramp metal removal	H. R. Cooper Assoc. Eriez Magnetics General Equipment & Mfg. Co. Inc.	Metramatic Corp. Outokumpu Oy Stearns Magnetics Inc. Tectron
Motion detectors	Allen-Bradley Banner Engr. Corp. Conveyor Components Co. Dynalco Corp. Gould Inc.	Material Controls Inc. Omron Electronics Inc. Ramsey Engr. Co. Veeder-Root
Variable-speed conveyor drives	General Electric Reliance Electric	Square D Company Westinghouse Electric
Variable-speed feeders	Allis-Chalmers Eriez Magnetics FMC Corp.	Jeffrey Mfg. Div., Dresser Industries Rexnord Inc.
Plugged chute detectors	Endress & Hauser Inc.	Magnetrol

Fig. 5—Mount Wright grinding circuit schematic



autogenous mill followed by a ball mill, rod mill followed by two ball mills in series, and a single-stage ball mill. These grinding circuit arrangements are representative of the majority of grinding systems currently being utilized and controlled.

A single-stage grinding circuit with an autogenous mill in closed circuit with screens for classification and particle size control (Fig. 5) is used at Quebec Cartier's Mount Wright operations,[4,5] a plant that is under computer control, with manual backup, from crusher feed through concentrate loading and tailings disposal. As the figure indicates, the parameters used for mill feed control (new ore) are the autogenous mill power draw and bearing pressure on the hydrostatic lubricated bearings. The new ore feed rate is controlled using mill power draw in a cascaded direct-digital control loop, thereby maintaining the mill power (kilowatt) set point. When hard ore is encountered, overloading results from the long response time in the ore feed-rate loop. To prevent overloading, the mill bearing pressure is used as a set point bias between the kilowatt control block and the tonnage control block. The latter is primarily for overload protection, as indicated by the diagram, and not for control.

For autogenous mills, maximum grinding efficiency is obtained at maximum power draft, Lynch indicates[9] (Figs. 6 and 7). Disturbance-effect relationships include: 1) an increase in feed rate at constant feed size and hardness

Fig. 6—Mill load vs. power consumption for an autogenous mill

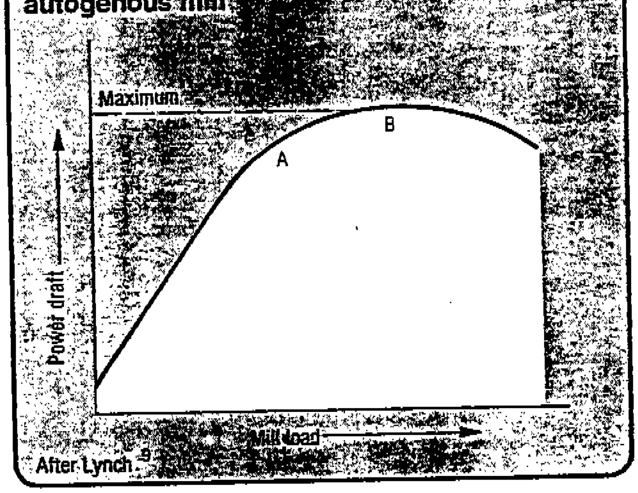


Fig. 7—Typical control system for an autogenous mill

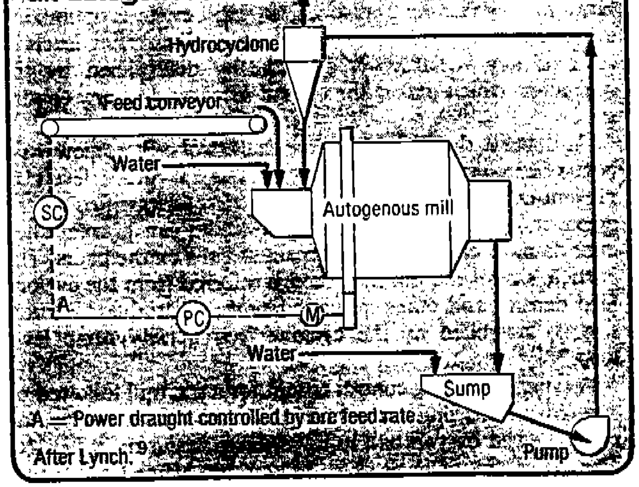
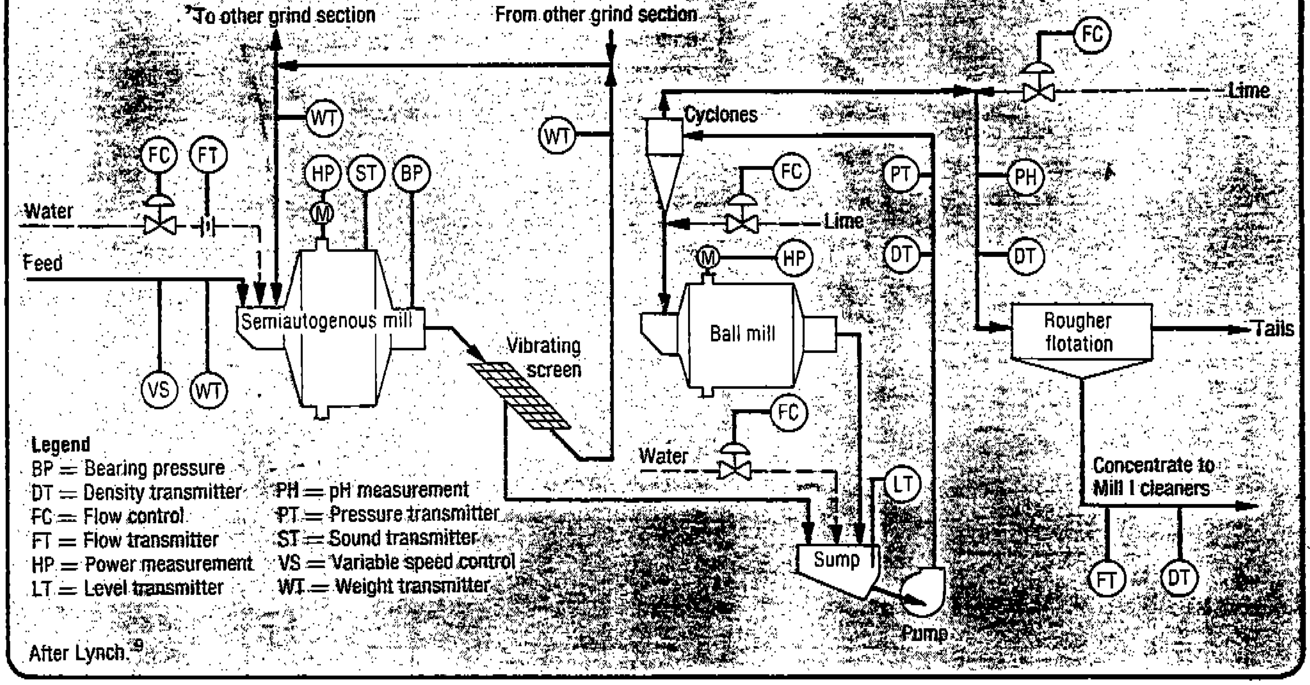


Fig. 8—Cyprus Pima Mining Co., Mill II (flowsheet and instrument diagram)



(grindability) causes an increase in the mill load and power draw, while variation in the particle size of the mill product would be minimal, 2) an increase in ore hardness at constant feed rate and particle size has an effect similar to an increase in feed rate, and 3) an increase in feed size at constant feed rate and hardness has the effect of increasing pebble wear rate and breakage of the smaller particles, thus giving a coarser product particle size.

The Cyprus Pima Mining Co. Mill II circuit is a well-documented example of a grinding circuit employing a semiautogenous mill followed by a ball mill[9,10] (Fig. 8). Because the ore hardness at the plant varies over a wide range, the objective of the control strategy is to maximize throughput without overloading either the semiautogenous mill or the subsequent ball mill.

Given the wide range of grindability and the possible variations in operating configurations between the two parallel grinding circuits at Cyprus Pima, three levels of control were instituted. Level 1 is local and applies when the control of the process is not directly influenced by the computer. Level 2 is operator-directed automatic control, which allows operator determination of parameters such as semiautogenous mill horsepower and solids targets. Level 3 is optimizing automatic control, where determination of operating levels of selected key variables is dynamically determined by the computer, which makes the system responsive to any contingency.

At Level 2, the operator, through control of horsepower set points, can implicitly control the mill inventory levels to prevent overloading. Mill solids can also be modified by the operator, and with soft ore, the operator can prevent shell liner damage caused by the impact of balls on the liners. The particle size of the flotation feed is inferred from the cyclone feed density and other measured process variables. Particle size is controlled by the cyclone feed density/sump level loop.

A typical grinding control circuit for a rod mill followed by one ball mill is illustrated in Fig. 9, and a circuit for a rod mill followed by two ball mills in series is shown in Fig. 10. The latter circuit is used at Mount Isa Mines, Australia.[9]

The control objectives for these circuits are to stabilize the operation and to maximize tonnage throughput at a predicted particle size. These objectives are achieved by controlling the rod mill feed water—and thus the discharge density, the cyclone feed-pump sump level, and the water additions to the cyclone feed-pump sumps—to maintain the circulating loads at maximum power draw.

For a single-stage ball mill grinding circuit, two instrumentation and control concepts are illustrated in Fig. 11. In the circuit at the left of the figure, control is based on maintaining a constant cyclone feed density using a fixed-speed-drive cyclone feed pump. At the right, the control system is based on maintaining a constant circulating load using a variable-speed-drive cyclone feed pump.

Fig. 9—Typical rod mill-ball mill grinding control circuit

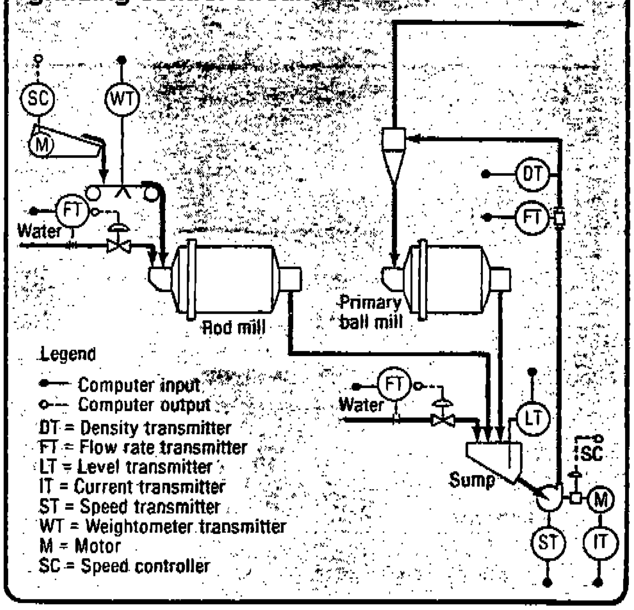
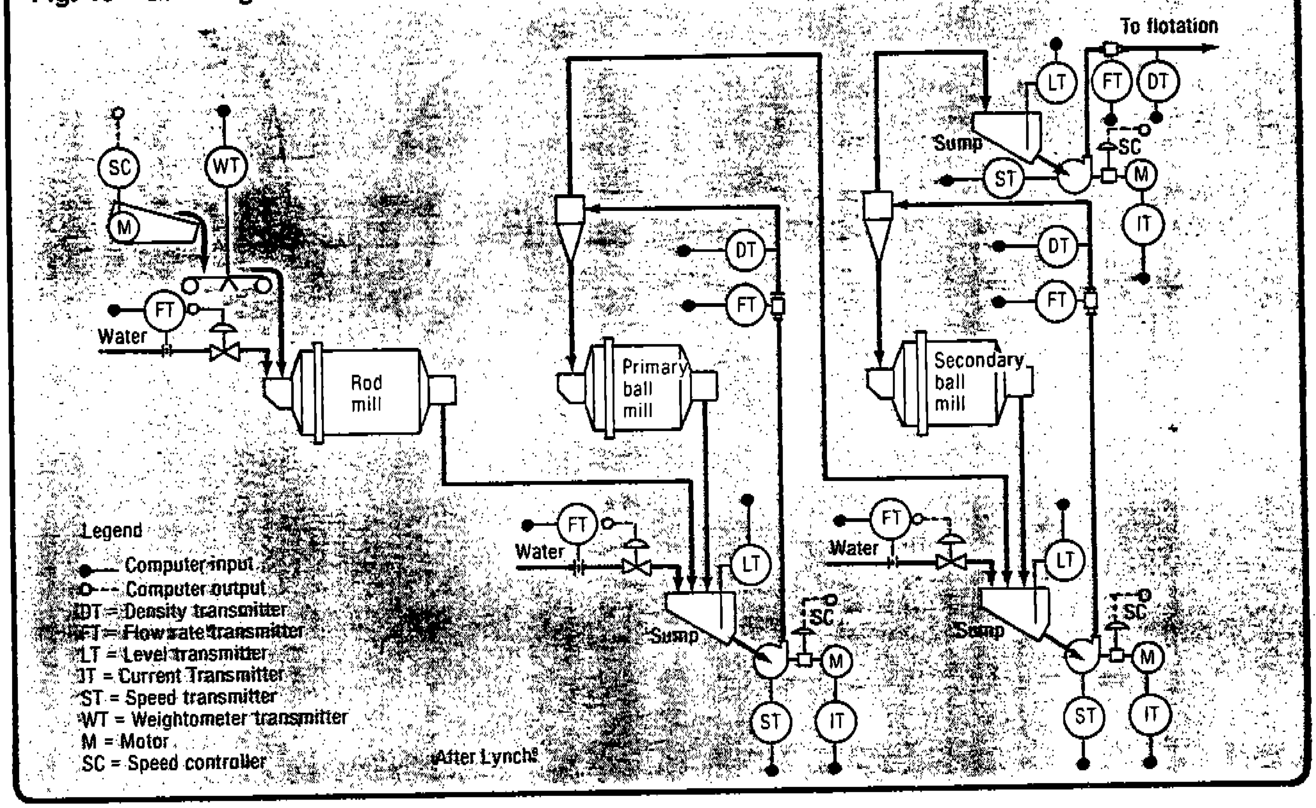


Fig. 10—Grinding control for rod mill followed by two ball mills in series



Control of other grinding-classification circuits usually would follow the concepts outlined in the examples above. The specific instrumentation and control strategies would be dependent on the control objectives for the individual grinding circuit.

In addition to the instrumentation indicated in Figs. 5-11, sound detectors are frequently used, although not so much for control as to provide operator information. An exception is Brenda Mines Ltd., B.C., Canada, where mill sound is used in the control system to infer liner wear in the rod mills and thus predict liner changes.

The particle size monitor is another device used for measurement and control. In some systems, direct measurement of particle size is used in control loops. In a number of instances,[2,9,10,12] particle size in the cyclone overflow is predicted or inferred from an empirical model of the individual cyclone, based on selected process variables. The generalized model is based on the work of Rao, et al.[9]

FLOTATION

Flotation circuit instrumentation usually includes pulp level control, slurry density control, flotation air control of air pressure or airflow rate, reagent flow control, and froth level

Fig. 11—Single-stage ball mill grinding circuit showing two control concepts

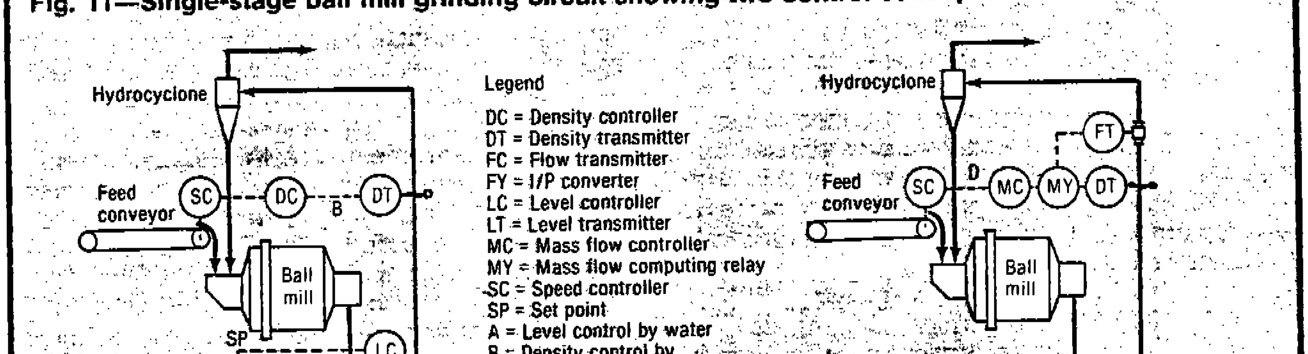
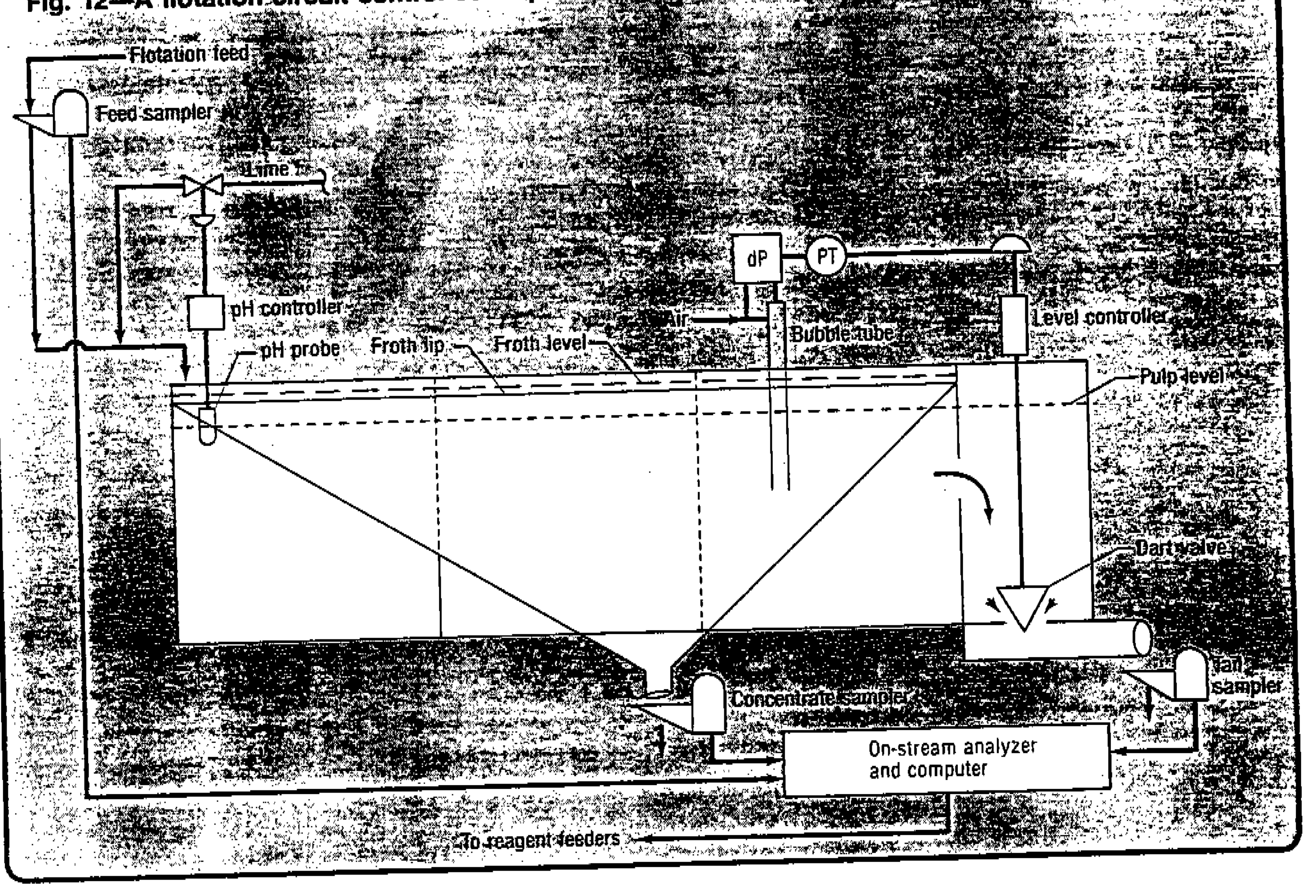


Fig. 12—A flotation circuit control concept



control. However, all of these control elements are not available in every plant.

Pulp level control is generally based on pulp level detection, and use of either a movable weir or dart valves with positioners similar to water control valves for control. Pulp level is detected by bubble tubes, as is the case for detecting some slurry sump levels in grinding circuits. Over the years, a number of other pulp level detection devices also have been used, including: floats submerged in the froth, which eventually become covered with minerals and become ineffective; capacitance probes, which have the same problem as the floats; and sonic level detectors, which may fail as a result of false readings arising from froth characteristics that differ from pulp characteristics.

Flotation air is commonly controlled manually by gate, plug, or slide valves, depending on the manufacturer of the machine. The air can be controlled automatically but usually is not.

The pH flotation circuit slurry is monitored with pH meters that operate reagent feeders, which add either a base or an acid, depending on the flotation requirements. Most pH control circuits are independent of other control loops;[13] however, they can be incorporated into the overall computer-based control system. With the advent of on-stream X-ray fluorescence spectrometers in the 1960s, reagent control based on current events became a reality.

A flotation circuit control concept is illustrated in Fig. 12. Lime addition is adjusted by a pH controller. The pulp level and consequently the froth level are controlled by adjustment of the dart valve in the tailing stream. The composition of the feed, concentrate, and tailing are measured by an on-stream X-ray analyzer, and these data are then used to control the amount of reagent injected into the system to produce the desired metallurgical performance.

FLOAT AND GRIND INSTRUMENTS

Instrumentation used in grinding and flotation circuits includes bearing pressure detectors, water control valves, water flow measurement, slurry flow measurement, slurry level detectors, slurry density sensors, mill sound measurement, particle size sensors, pH monitors, and onstream X-ray analyzers. Table 2 is a partial list of the manufacturers and suppliers of these types of instrumentation. Although not all-inclusive, the list is intended to indicate the wide availability of process instrumentation for grinding and flotation circuit applications. Various manufacturers supply analog or computer-based control systems used in grinding and flotation circuits, including Bailey Controls, Fisher Controls, Fischer & Porter Co., Foxboro Co., Honeywell, Leeds & Northrup Co., Moore Industries, Outokumpu Oy, Rochester Instrument Systems, Rosemont Inc., Taylor Instrument Co., and Westinghouse Electric Corp.

GRAVITY CONCENTRATION

Gravity concentration circuits commonly contain one or more of the following types of concentrators: spirals, Reichert cones, and shaking tables. Little process control is applied in such circuits other than slurry density, mass flow, and wash-water addition, and even these variables are usually monitored visually and adjusted manually. Computer-based process control is used, however, at the Mount Newman, Australia, beneficiation plant, which includes a Reichert cone gravity-concentration section for upgrading iron ore.

Table 2—Manufacturers and suppliers of grinding and flotation circuit instrumentation

Instrumentation	Manufacturers and suppliers	
Mill bearing pressure detectors	Ernst Gage Co. The Foxboro Co. Honeywell Koppers Co.	Micro-Strain Inc. Moore Products Co. Taylor Instrument Co. Uehling Instrument Co.
Water control valves	Crane Co. Fisher Controls The Foxboro Co.	Jamesbury Corp. Masoneilan Int. Inc. Robertshaw Controls Co.
Water flow measurement	Fischer & Porter Co. The Foxboro Co. Honeywell Meriam Instruments	Robertshaw Controls Co. Taylor Instrument Co. Westinghouse Electric
Slurry flow measurement		
Magnetic type	ACCO, Bristol Div. Brooks Instrument Fischer & Porter Co.	Fischer Controls The Foxboro Co. Honeywell
Sonic type	Controlotron Corp. Leeds & Northrup Co. MAPCO Inc.	Micro-Motion Inc. Polysonics Robertshaw Controls Co.
Slurry level detectors	C-E Invalco Controlotron Corp. Endress & Hauser Inc.	Envirotech Corp. The Foxboro Co. Robertshaw Controls Co.
Slurry density sensors	Kay-Ray Inc. Micro-Motion Inc.	The Ohmart Corp. Texas Nuclear Div., Ramsey
Mill sound measurement	Koppers Co.	Milltronics Inc.
Particle size sensors	ARMCO Autometrics The Foxboro Co.	Leeds & Northrup Co.
pH monitors	ACCO, Bristol Div. Beckman Instruments Inc. Fischer & Porter Co. The Foxboro Co.	Great Lakes Inst. Co. Leeds & Northrup Co. Robertshaw Controls Co. Taylor Instrument Co.
On-stream X-ray analyzers	Amdel Applied Research Labs Bondar-Clegg & Co. H. R. Cooper Assoc.	NEC Products—Envirotech Corp. Outokumpu Oy Phillips Elect. Inst. Inc.

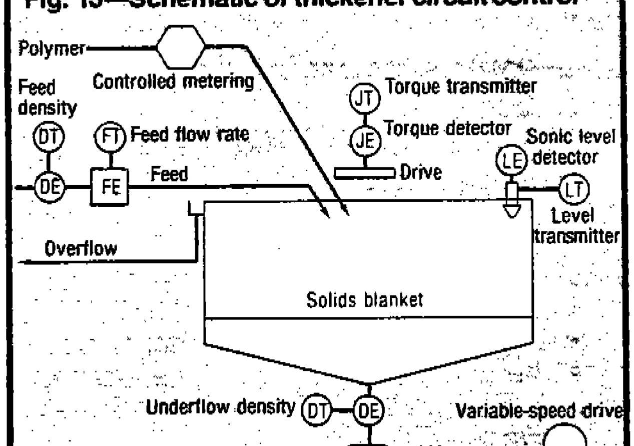
THICKENING

The objectives of thickener control are varied, but in most instances, the objective is to dewater the slurry, reclaim the clear overflow for reuse in the process, and produce a thickened or more dense underflow, which can either be rejected, in the case of tailings, or used as feed for subsequent unit operations.

The general control elements for a thickener are shown in Fig. 13. By knowing the feed density, feed flow rate, underflow density, and underflow flow rate, the solids in, solids out, and solids inventory in the thickener can be maintained by adjusting the pump speed. Overrides, or limits, to the controlled variables are underflow density, drive torque, and solids inventory level. If the flow out is less than the flow in, the pump speed will not increase unless the density is such that the drive-torque upper limit or the maximum solids inventory has been reached. If the flow out is greater than the flow in and the outflow density is lower than desired, the pump speed will be decreased, provided the drive-torque limit is within a safe operating range and the solids inventory is below the upper limit. The polymer feed rate will be controlled by using a variable-speed calibrated metering pump based on the solids and volume in the feed.

This thickener system would be difficult to control automatically with analog instruments and controllers, because of the decisions that are required. It could be operated with good stability by using a computer-based controller that included the necessary limiting logic.

Fig. 13—Schematic or thickener circuit control



FILTRATION

Filter controls, if used, are usually limited to feed rate (volume) and for drum or disc filters to tub level control. The sensing, transmitting, and control devices are the same as described for handling slurry levels and flows.

DRYING

Dryer controls depend on the type of dryer to be used and the material to be dried. For direct-fired dryers using oil or gas burners, the inlet air temperature and the outlet air temperatures can be used to develop a control strategy. If multiple burners are used at different locations or zones in the dryer, the zone temperatures can also be used in the control strategy. This concept of controlling a dryer usually requires that an empirical model of the dryer be developed, and, according to Shinskey,[15] the general control equation would be based on the following relationship:

$$K = (To\text{-}Tw)/(Ti\text{-}Tw)$$

where the ratio K is a function of the physical characteristics of the dryer, the properties of the solid and liquid phases, and

the final moisture content of the dried product, and
To = outlet temperature,
Ti = inlet temperature of heated air, and
Tw = wet-bulb temperature.

Depending on the dryer design, wet-bulb temperatures and in some cases inlet temperatures of heated air are difficult to obtain.

For dryers that use steam or other heat transfer media in a closed circuit (the media is not in direct contact with the material being dried), the pressure of the steam and the flow rate of the steam (in the case of steam) can be used to develop the control strategy. For liquid heat transfer media (Dowtherm, Therminol, etc.), the temperature drop of the media in the dryer, the flow rate of the media, and the flow rate of the material to be dried can be used to develop the control strategy. In essence, each dryer control strategy is unique and requires that the thermodynamic properties of both the material being dried and the moisture-extracting media, either hot air or heat transfer media, be known as well as the characteristics of the dryer itself.

Thermocouples, resistance temperature detectors, and capillary tube elements, common types of temperature-sensing devices used for dryer controls, are available from many instrument manufacturers.

INDUSTRIAL APPLICATIONS

The economic justifications for instrumentation and process control are potential improvements in productivity (increased throughput, recovery, or both), reduction in operating costs through energy and raw material conservation, and improved process stability. When considering the overall design and implementation of instrumentation and process control for a new plant, it is beneficial to examine some recent applications in the minerals industry (Tables 3-5). The economic benefits derived through process control are included for the various applications cited.

The relationship of control to the process itself, to measurement, and to process optimization can be described as follows: measurement of a process variable may be made either to monitor the variable or to control it at a specific level; to optimize the process, the level of one or more process variables must be controlled at a desired condition.

When looking at the individual applications cited in the tables, one must keep in mind that the control objectives and degree of complexity of the control systems differ for the various applications. Although measurement of the process variables and control of the processes were achieved for the different installations, degree of process optimization varied widely.

Fig. 14—Capacitance-type level indicator

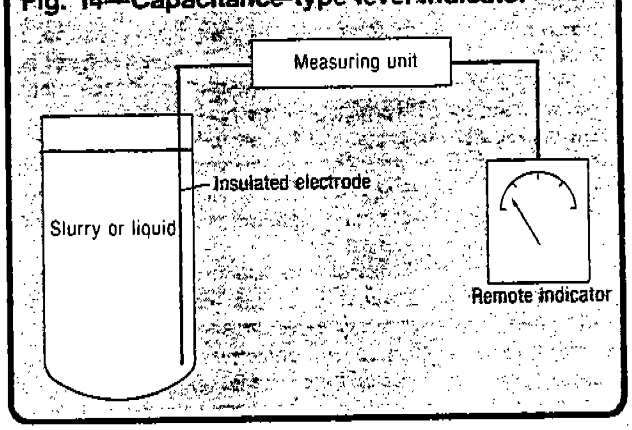


Table 3—Crushing plant control system applications

Property & crushing circuit	Capacity (stpd)	Improvement cited
Climax Molybdenum Co. [20, 21] Tertiary crushing in closed-circuit with screens (10 circuits)	50,000	Improved throughput and power utilization
Duval Sierrita Corp. [19] Three-stage crushing, final stage in closed-circuit with screens	86,000	Increased throughput in excess of 14,000 stpd
International Nickel Co. [22] (Frood-Stobie mill) Double-deck screen, standard cone crusher; double-deck secondary screen, shorthead cone crusher (4 circuits)	24,000	Improved throughput
Mount Isa Mines, Ltd. [9] (No. 2 concentrator) Two-stage crushing, each stage with closed-circuit screens	15,000	Improved throughput and product quality, reduced operating manpower
Mt. Newman Mining Co. [14] Crushing, screening, gravity separation	20,000	Initial installation
Quebec Cartier Mining Co. [4, 5] (Mount Wright) Gyratory crusher	140,000	Maximizes throughput
Texasgulf Inc. [23] (Ecstall—Kidd Creek) Secondary and tertiary crushing	10,000	Initial installation

CRUSHING PLANT CONTROL

The potential for reducing the capital and operating costs for crushing circuits has been discussed by Flavel,[16,17] who outlines control of the use of crushing energy in crushing and screening circuits and suggests a crusher-control system to accommodate the important process parameters. Techniques for automating various types of crushing machinery have been described by Motek,[18] in addition to those previously cited. Depending upon the operating conditions, automatic control of crushing systems has resulted in varying degrees of increased production and decreased power consumption per unit of productivity.

Process control strategies for a three-stage crushing plant were evaluated by Kellner and Edmiston.[19] The functional relationships between production rate and process variables—including crusher setting, power draft, mantle support pressure, feed size, ore type, mantle and concave configuration, and crusher speed—were defined for the Duval Sierrita Corp. crushing plant in Arizona. These relationships provided a basic understanding of the crushing process and a basis for defining the various control strategies considered for evaluation. The control objectives were to maximize production rate and to balance the load between the secondary and tertiary crushers. The control system was designed so that any of the three main control parameters—feed rate, power input, and close-side setting—could be selected as the independent variable. The production capability of the crushing plant was increased from about 72,000 stpd to more than 86,000 stpd as a result of the intensive effort devoted to achieving a better understanding of the crushing operations and applying that understanding to a control system. Based on the plant-scale investigation, modifications were also made to the existing crushing equipment to augment and further enhance productivity.

Table 4—Grinding circuit control system applications

Property & type of grinding circuit	Capacity (stpd)	Improvement cited
Amax Lead Co.[25] (Buick mill) Rod mill, ball mill, hydrocyclone	6,000	3-5% throughput; process stabilization
Asarco, Inc.[12,26] (Silver Bell) Grate ball mill, hydrocyclone	11,000	6% throughput; process stabilization
Bougainville Copper Ltd.[9] Ball mill, hydrocyclone	90,000	Improved throughput; process stabilization
Brenda Mines Ltd.[11,27] Rod mill, ball mill, hydrocyclone	30,000	10% throughput
Cities Service Co.[28,29] (Pinto Valley) Ball mill, hydrocyclone	40,000	Not reported; in development stage
Climax Molybdenum Co.[2,3,30] (Climax) Ball mill (grate & overflow), spiral classifier, hydrocyclone	48,000	4.4% throughput; process stabilization
Craigmont Mines Ltd.[31,32] Rod mill, ball mill, hydrocyclone	6,000	6% throughput; controlled grind size; increased Cu recovery
Cyprus Pima Mining Co.[9,10,33] (Mill II) Semiautogenous mill, ball mill, hydrocyclone	18,400	10% throughput; process stabilization
Goldfields of South Africa Ltd.[34] (West Driefontein mine) Rod mill, pebble mill, hydrocyclone	9,700	Particle size control; reduced gold losses
Lornex Mining Corp. Ltd.[35] Semiautogenous mill, ball mill, hydrocyclone	48,000	7.5% throughput; process stabilization
Mount Isa Mines Ltd.[9] (No. 2 concentrator) Rod mill, ball mill, hydrocyclone	8,000	5% throughput
Mount Isa Mines Ltd.[9] (No. 4 concentrator) Rod mill, ball mill, hydrocyclone	19,500	5% throughput
New Broken Hill Consolidated Ltd.[9] Rod mill, ball mill, rake classifier	5,000	1.8% lead recovery; 1.5% zinc recovery; stabilized operation
Outokumpu Oy[36] (Pyhasalmi mill) Two-stage autogenous mill (lump & pebble mills), hydrocyclone	3,400	6% throughput; process stabilization and optimization
Phelps Dodge Corp.[1] (Morenci) Grate ball mill, spiral classifier	60,000	2.5% throughput
Quebec Cartier Mining Co.[4,5] (Mount Wright) Autogenous mill, two-stage screening	100,000	Optimized mill throughput
Renison Ltd.[9] Ball mill, wedge-wire screen	2,100	5% throughput; process stabilization
Texasgulf Inc.[23] (Ecstall—Kidd Creek) Rod mill, ball mill, hydrocyclone	10,000	Initial installation; results not reported
Utah Mines Ltd. (Island Copper) Semiautogenous mill, ball mill, hydrocyclone	38,000	Not reported; in development stage

Results from seven industrial applications of crushing plant control systems are summarized in Table 3, and details regarding these individual control systems are described in the references noted for the various installations. Overall, crusher control has tended to increase throughput rates and improve energy efficiency.

GRINDING CIRCUIT CONTROL

Over the past decade, appreciable attention has been given to grinding circuit control, especially because small improvements in circuit capacity result in significant cost benefits for this cost-intensive unit operation. In addition to the benefits that have been achieved from increased throughput and metal recovery, energy conservation[24] can play a major role in the economic justification for grinding circuit control systems. As energy costs continue to increase, the need to conserve energy becomes even more acute for engineers considering the overall design and operation of energy-intensive unit operations.

Different control strategies have been implemented for a variety of grinding circuit applications, and significant improvements in performance have been achieved throughout the minerals industries (Table 4). Although control objectives differed on a plant-to-plant basis, process stabilization and increased productivity were common goals. Data from various types of circuits indicate gains in grinding throughput rates varying from 2% to 10% following application of process controls, in addition to other benefits such as process stabilization, energy savings, and increased metal recovery.

FLOTATION CIRCUIT CONTROL

Numerous flotation circuits or portions thereof have been placed under automatic control over the past decade (Table 5), and preliminary research and development effort leading to flotation control is well documented in the literature, including recent articles on development of flotation control strategy for a nickel-bearing ore;[37] on the behavior of sulphide mineral processes, defining flotation mechanisms and the importance of the chemical environment on the process;[38] and on mathematical models used in the development of advanced computer control systems.[39] Early development of Outokumpu's flotation control systems has been described by Eerola and Paakkinen.[40] This work included theoretical studies of the process dynamics and control of the flotation process.

Recent developments in on-stream composition analysis sensors have greatly enhanced the capability of computer control of the flotation process. Plant trials of radioisotope immersion probes for on-stream analysis are described by Fookes, et al.[41] Accuracies obtained were considered to be adequate for process control. Instruments using isotopes to measure lead in mineral slurries can be based on the absorption of low-energy gamma rays, backscattering of beta particles, or X-ray fluorescence. The merits of each method are discussed by Kawatra,[42] and the reasons for selecting the beta-backscattering technique for an industrial concentrator are presented. Economic benefits derived from X-ray analysis techniques in copper milling have been defined by Cote,[43] and payback of an X-ray installation has been achieved within one year.

Reagent and pH control are also incorporated in many flotation control systems.

The benefits derived from flotation control vary from plant to plant, depending on control objectives; however, a significant impact has usually been made on the overall plant economics in the form of increased recovery, reduced operat-

Table 5—Flotation circuit control system applications

Property & flotation circuit features	Valuable metal	Improvement cited
Brenda Mines Ltd.[27] Copper-molybdenum flotation circuits, computer-based flotation control system	Copper molybdenum	Development stage, aimed at maximizing recoveries
Cities Service Co.[44] (London Mill, Tenn.) Pyrrhotite-copper-zinc flotation circuits, reagent and flotation control	Iron sulphide, copper, zinc	Reagent savings and improved metallurgy
Falconbridge Nickel Mines Ltd.[45, 46] (Lake Dufault mill) On-stream X-ray analysis computer system	Copper, zinc	Improved recoveries and product quality: benefits about $450,000/year
Falconbridge Nickel Mines Ltd.[45, 46] (Strathcona mill) On-stream X-ray analysis, reagent and pH control, computer system	Copper, nickel	Reagent savings; positive feed blending; 1.5% recovery
Hudson Bay Mining & Smelting Co.[49] (Flin Flon) On-stream X-ray analysis and computer control of flotation circuits	Copper, lead, zinc	Reagent savings; improved metallurgical performance
International Nickel Co.[50, 51] (Clarabelle mill) On-stream analysis and computer control of flotation circuits	Copper, nickel	Improved product quality; 1.6% conc. grade; 2.3% recovery
International Nickel Co.[22] (Frood-Stobie mill) On-stream analysis and computer control of flotation circuits	Copper, nickel	Improved metallurgical performance; stabilized process
Kennecott Copper Corp.[13] (McGill) Copper flotation circuit with pH control	Copper	Reduced lime consumption and improved metallurgical control
Mattagami Lake Mines Ltd.[52] On-stream X-ray analysis and computer control of flotation circuits	Copper, zinc	Improved flotation efficiency; reagent costs decreased; 1% zinc recovery and 0.4% zinc grade; $624,000/year
Mount Isa Mines Ltd.[9, 53, 54] (No. 4 concentrator) On-stream X-ray analysis and computer control of flotation circuits	Copper	10% reduction in collector; process stabilization; consistent product quality
New Broken Hill Consolidated Ltd.[9, 55, 56] On-stream analysis and computer control of flotation circuits	Zinc, lead	1.8% lead recovery; 1.5% zinc recovery
New Jersey Zinc Co.[57] (Friedensville mill) On-stream X-ray analysis for zinc flotation circuits	Zinc	Reduced reagent usage; $33,000/year; improved metallurgy; 2.1% zinc grade
Outokumpu Oy[58-60] (Keretti mill) On-stream analysis and computer control of flotation circuits	Copper, zinc	Reduced reagent usage; increased recoveries; net benefits about $460,000/year
Outokumpu Oy[61-63] (Kotalahti mill) On-stream X-ray analysis and computer control of flotation circuits	Nickel, copper	Process stabilization and optimization; 1.7% Ni and 1.9% Cu recoveries
Outokumpu Oy[36, 61, 64] (Pyhasalmi mill) On-stream X-ray analysis and computer control of copper zinc, and pyrite flotation circuits	Copper, zinc, iron sulphide	Maximized recoveries; improved economic results
Outokumpu Oy[59, 64, 65] (Vuonos mill) Computer control and stabilization of flotation circuits	Nickel, copper	Reduced costs and increased productivity
Texasgulf Inc.[66-69] (Ecstall—Kidd Creek) On-stream X-ray analysis and computer control of flotation circuits	Copper, lead, zinc	Reduced reagent costs; improved concentrate grade; 1.1% Cu and 1.4% Zn recoveries; savings $1.5 million/year

ing costs, improved product quality, process stabilization, or a combination of these features.

COMPUTER-BASED CONTROL

A list of computer-based control systems based on information obtained from the literature and provided by various computer manufacturers is presented in Table 6. Although not all-inclusive, the list illustrates the variety of computer hardware used in the minerals industry.

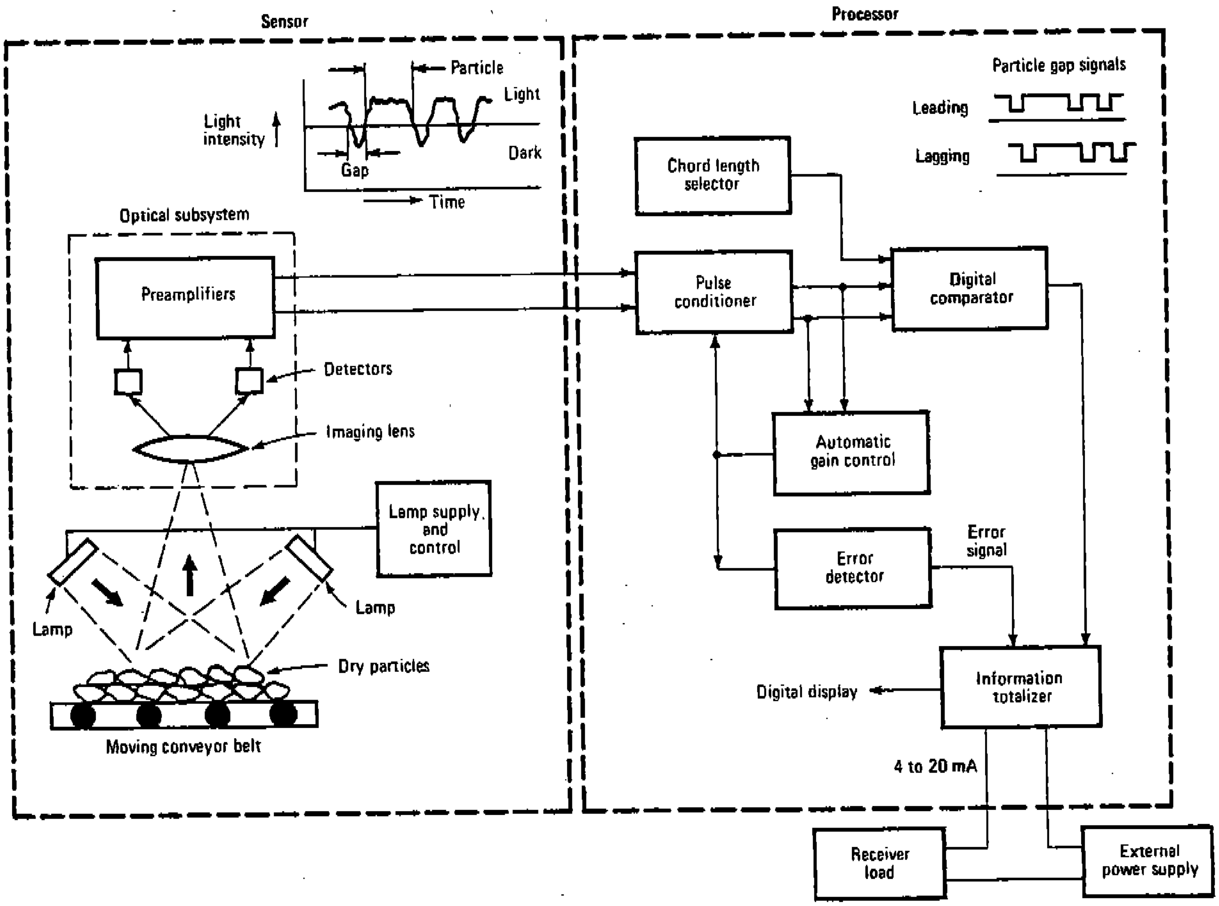
OUTLOOK FOR THE 1980s

Recent advances in measurement technology have been significant, and as a result, our capability for measuring process variables in the 1980s is enhanced. For example, in addition to the more traditional magnetic flowmeter, noncontact measurement devices are available for basic flow measurement, using ultrasonic technology. Three general systems are available:[70] the Doppler system, the leading-edge system, and the frequency-difference system. These systems are based on the principle that when a sound wave is transmitted against the direction of flow, it is slowed down, and with the direction of flow, it is speeded up. The Doppler system, which can measure slurry flow rates, is based on the fact that when sound waves are reflected from moving objects, the frequency of the reflected beam differs from that of the incident beam. Consequently, the particle velocity, which is proportional to frequency change, can be determined. The leading-edge and frequency-difference systems are applicable to liquid flow rates.

Numerous instruments are available for measuring sump level in slurry systems, yet this apparently simple measurement has been very troublesome in many instances. Capacitance-type level detectors, which offer high reliability, are replacing other devices for sump level control. (An example of a capacitance-type level indicator is illustrated in Fig. 14.) The capacitance system is passive, having no moving parts, and can be made compatible with a wide variety of slurries, liquids, and tank shapes. It is fairly low cost when compared with alternate electronic or pneumatic sensors.

In addition to conventional gamma gauges, ultrasonic devices have been developed to measure slurry density. Ultrasonic energy transmitted through a slurry is attenuated

Fig. 15—Simplified block diagram of particle size distribution transmitter



Source: The Foxboro Co.

as a function of suspended solids and transmission paths, the more dense the slurry or the longer the transmission path, the greater the energy loss. The Armco Autometrics particle size monitor has used this technique for some time to measure slurry density in conjunction with particle size. Other instrument manufacturers also offer ultrasonic sensors for slurry measurement.

On-stream measurement of particle size distribution has received considerable attention. The Leeds & Northrup "Microtrac" system for on-line measurement of particle size distribution in wet slurry and dry powder streams[71] makes use of low-angle forward light scattering (Fraunhofer diffraction) to determine the size distribution of particles moving through a laser beam. A multiple-segment histogram of the particle size distribution between 2 and 176 micrometers can be formulated, as well as mean diameter and surface calculations. The iron and cement industries are among the initial users of these monitors.

Foxboro's optical instrument for measurement of the size distribution of coarse particles illuminates the surface of the material being measured with light at low angles, thereby casting shadows along the line of observation (Fig. 15)[72]. The light intensity pattern generated allows discrimination of the particles, and the particle chord length can be measured. A single- or six-output signal unit is available, with each output representing the cumulative percent of chord length less than a selected particle size ranging from 3 to 300 mm.

In composition analysis, submersible X-ray probes using radioisotopes have been introduced successfully in several Australian mills.[41] While X-ray analyzers have been in use for many years, the piping requirements to bring slurry samples to a central unit have represented a sizable investment. Many successful installations of this type exist, but the potential advantages of simplified installations using the in-stream probe concept are obvious. Scintillation detector probes and nitrogen-cooled solid-state detector probes are offered by Amdel, Bondar-Clegg & Co. Ltd., NEC Products-Envirotech Measurement Systems, Outokumpu Oy, and other companies. Thermoelectric cooled, solid-state detector probes are in the development stage, and these devices should be commercial in the near future.

Also in the future, measurement of ore type—for example, degree of oxidation or iron content—may be feasible using an optical sensor to monitor color. Correlation of ore color and copper recovery has been demonstrated at the Phelps Dodge Corp. Morenci operation.[73] This type of process information has potential application in feed-forward control of the flotation process.

Other areas gaining attention include measurement of the apparent slurry viscosity, an important process variable in wet tumbling-type mills, and the use of load cells to obtain a direct measure of mill loading, especially in autogenous and semiautogenous mills. Techniques for obtaining these measurements could play an important role in future grinding circuit control systems.

The development of microprocessors that have ample memory makes it possible to alter control system architecture and provide high-performance distributed-control systems. With advances in integrated circuit technology, hardware costs have been reduced, and by using serial transmission of the process signals for distributed-control systems instead of the extensive wiring requirements for a central control system, installation costs have also been decreased.

In the future, the availability of mass memory storage to replace disc or drum storage will improve control system reliability and performance.

Also, small, single-purpose computers will be increasingly used for specific control tasks. For example, a unit could define the process model for a hydrocyclone and be used for controlling the operation of different hydrocyclone classification circuits following specification of the input and output parameters. The concept of single-purpose computers is expected to find application in various unit operations and to be very cost-effective for implementing process control strategies.

In summary, the economic need for process control in new plants is more important now than ever before, as stringent operating constraints arise from decreasing ore grade, rising energy costs, and pollution regulations. At the same time, control systems are being offered that are more flexible and easier to maintain, while providing greater capability at less cost than earlier versions—a development resulting from technological advances that include single-chip microprocessors. The reliability of sensors has been enhanced, and new sensors are being developed that should further expand control capabilities for mineral processing plants.

When designing new mineral processing plants, the importance of adequate instrumentation and process control must certainly be considered. A variety of approaches have been employed, and in all probability, no single, universally accepted procedure can be developed. It can be anticipated, however, that further experience will result in even more efficient and more effective approaches for bringing mineral processing operations under computer control.■

Table 6—Computer-based control systems in the minerals industry

Milling operation	Location	Computer
Amax Lead Co.	Boss, Mo.	Fisher Controls
Asarco Inc.	Silver Bell, Ariz.	Hewlett-Packard
Bougainville Copper Ltd.	Papua New Guinea	Digital Equipment Co.
Brenda Mines Ltd.	Canada	Fisher Controls
Brunswick Mining & Smelting Co.	Canada	Proscon (Outokumpu)
Cities Service Co.	Pinto Valley, Ariz.	Hewlett-Packard
Climax Molybdenum Co.	Climax, Colo.	Foxboro
Companhia Vale Do Rio Dore	Brazil	Foxboro
Cyprus Pima Mining Co.	Tucson, Ariz.	Accuray Corp.
Duval Corp.	Sahuarita, Ariz.	Digital Equipment Co.
Hammersley Iron Pty.	Australia	Foxboro
Heath Steele Mines Ltd.	Canada	Proscon (Outokumpu)
International Nickel Co.	Canada	IBM
Kudremukh Iron Ore Co. Ltd.	India	Foxboro
Lornex Mining Corp. Ltd.	Canada	Foxboro
Mount Isa Mines Ltd.		
No. 2 Concentrator	Australia	Foxboro
No. 4 Concentrator	Australia	Hewlett-Packard
Mt. Newman Mining Co.	Australia	Honeywell
New Broken Hill Consolidated Ltd.	Australia	Digital Equipment Co.
Outokumpu Oy		
Keretti mill	Finland	Proscon (Outokumpu)
Kotalahti mill	Finland	Proscon (Outokumpu)
Pyhasalmi mill	Finland	Honeywell
Vihanti mill	Finland	Proscon (Outokumpu)
Vuonos mill	Finland	IBM
Phelps Dodge Corp.	Morenci, Ariz.	IBM
Quebec Cartier Mining Co.	Canada	Foxboro
Renison Ltd.	Australia	Foxboro
Reserve Mining Co.	Silver Bay, Minn.	Honeywell and Digital Equipment Co.
Texasgulf Inc. (Ecstall)	Canada	Honeywell
U.S. Steel Corp. (Minntac)	Virginia, Minn.	Honeywell
Utah Mines Ltd. (Island Copper)	Canada	Fisher Controls

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