

FUZZY LOGIC EXPERT SYSTEM FOR

IRON ORE PROCESSING

Maynard B. Hall, C. Anthony Harris

Comdale Technologies (Canada) Inc.
833 The Queensway
Toronto, Ontario
M8Z 5Z1

ABSTRACT

This paper describes the implementation of an expert system for monitoring and control of the No. 4 autogenous mill and spiral circuits at Wabush Mines.

This process control system incorporated the mill operating expertise of Wabush Mines operating personnel and was implemented to improve spiral iron recovery and mill productivity by:

1. Continuously monitoring the mill power draw and ensuring that the mill feedrate is regulated to prevent damage to the mill motor, while simultaneously maintaining the feedrate at or as close as possible to the maximum feedrate determined by the process supervisor.
2. Improving control over the spiral density and feed rate.
3. Improving control over both the rougher and cleaner wash water.
4. Reducing the frequency with which pumps are plugged.
5. Allowing modifications to be made easily and quickly to test various operating strategies.

This system was installed using COMDALE/C, a real-time Expert System for Process Control. It was readily accepted by the process operators and produces higher production performance in comparison to the other 5 parallel mill lines at a lower power draw.

INTRODUCTION

Mineral processing unit operations such as grinding, flotation and dewatering are difficult to control because of:

- _ varying characteristics of process inputs
- _ long time lags
- _ varying responses to process loads
- _ highly non-linear relationships between process inputs and outputs
- _ lack of sensor equipment

Supervisory Control of grinding circuits have been interfaced to Level 1 control hardware as follows:

Level 2	Supervisory
	Trending, Historical data, Reporting, Supervisory Control
Level 1	PLC/DCS
	Analog and Digital Control functions
Level 0	Instrumentation
	Field Sensors, Final Control Elements

Many approaches to supervisory control of grinding circuits with varying levels of success have been reported [1], [2], [3]. This paper describes the successful application of expert systems technology for control of the grinding circuit at Wabush Mines.

THE PLANT

Wabush Mines is located in southwest Labrador, Canada. The mine is based on a 5.5 square mile specular hematite deposit. The plant started operation in 1965 and has a current rated production of 4.5 million tons of iron concentrate per year. Wabush Mines also operates pelletizing facilities near Sept. Isles, Quebec, Canada.

THE PROCESS

Run of mine ore is fed to 24' x 8' 1750 hp autogenous grinding mills. The mill discharge is screened, with the oversize going to a recirculating pump box then back to the mill. The undersize goes to the spiral feed pump box then to 2 stage spiral separation. Spiral midlings are combined in the recirculating pumpbox, and thus go back to the mill. Concentrate from the spirals go to the high tension plant.

There are six parallel mill/spiral lines numbered 1 to 6. The expert system was developed to control mill/spiral line #4.

Figure 1 shows the flowsheet of the grinding circuit.

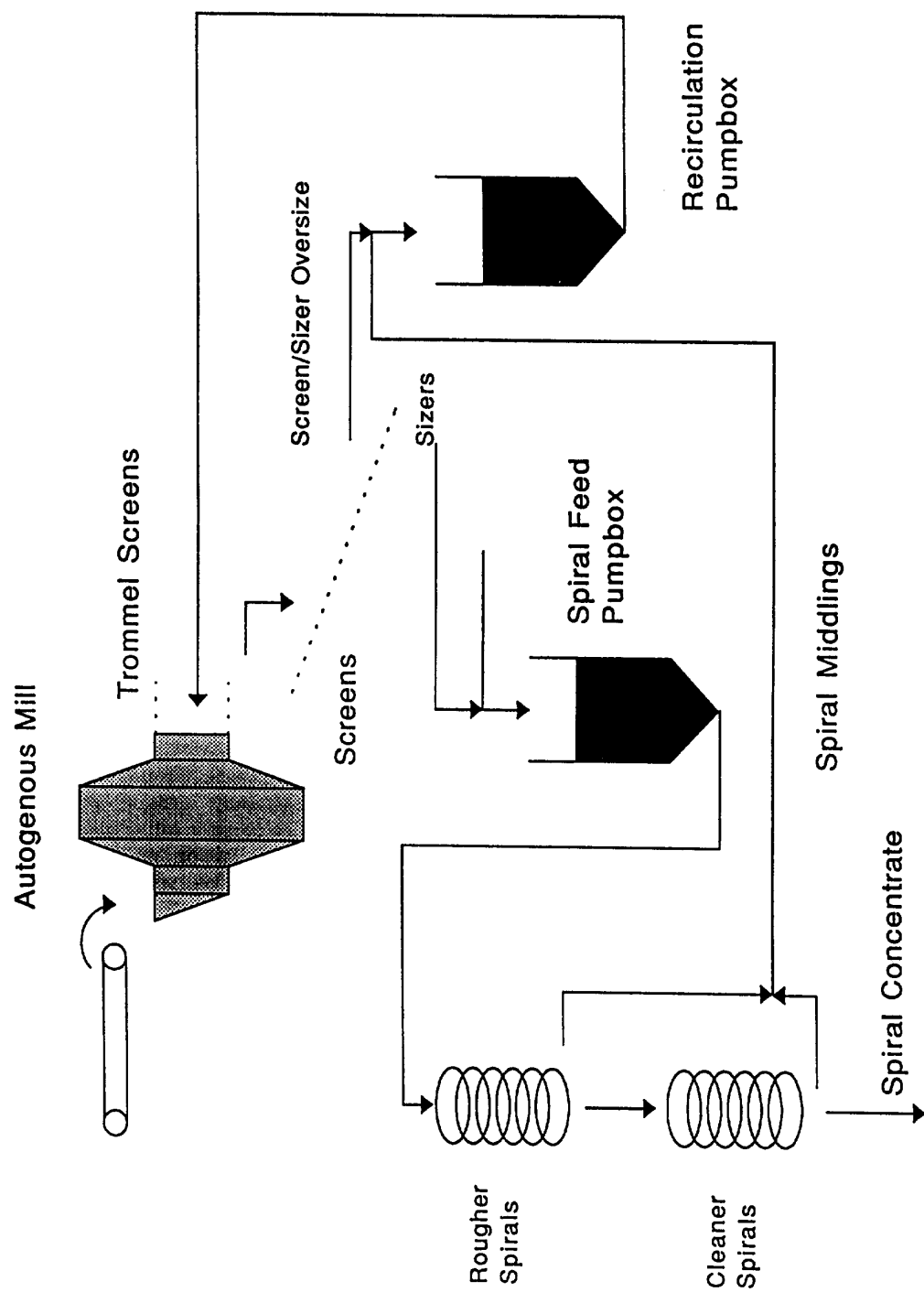


Fig 1. Circuit Flowsheet.

PROCESS PARAMETERS

Operation and control of mill line #4 consists of:

- _ setting and maintaining mill feedrate
- _ setting and maintaining water addition to the AG mill
- _ setting and maintaining water addition to the recirculating pump box
- _ setting and maintaining water addition rates to the spiral feed pump box
- _ setting and maintaining spiral wash water rates.

Operation also consists of monitoring and controlling:

- _ mill powerdraw
- _ recirculating feed parameters such as flow, density and pump box level
- _ spiral feed parameters such as flow, density and pump box level
- _ high tension plant product grade and recovery.

OBJECTIVES OF THE CONTROL SYSTEM

The objective of the expert system project was to develop a knowledge base containing a control strategy for Mill Line No. 4, this knowledge base, or control strategy, should improve the performance of Mill Line No. 4 and should be easy to modify in order to optimize the performance.

In order to achieve the objective the following goals had to be realized:

- (i) The expert system should continuously monitor the mill powerdraw and ensure that the mill feedrate is regulated to prevent damage to the mill motor, while simultaneously maintaining the feedrate at or as close as possible to the maximum feedrate determined by the process supervisor.
- (ii) The expert system should improve control over the spiral density and feed rate.
- (iii) The expert system should improve control over both the rougher and cleaner wash water.
- (iv) The expert system should reduce the frequency with which pumps are plugged.
- (v) The knowledge base should be structured so that modifications can be made easily and quickly without the need for rewriting the entire system.

An optimum grind control strategy is achievable by incrementally improving the degree to which the above goals are met.

This expert process control system was installed using the COMDALE/C Real-Time expert system development tool

from Comdale Technologies (Canada) Inc., Toronto, Canada.

SCOPE OF PROJECT

The scope of the work performed by Comdale Technologies (Canada) Inc. consisted of:

1. Provision of the software interface to the process input/output
2. Provision of the expert system development software
3. Provision of the operators' interface to the process
4. Configuration of the process graphical display screens
5. Provision of trends, bars and instantaneous group displays for all analog variables and faceplate displays for all primary loops
6. Development of the expert system's knowledge base that contains an operating strategy for Mill Line No. 4.
7. Installation and commissioning of the expert system application
8. Provision of on-going technical support.

Wabush Mines personnel installed the sensors, Foxboro 761 single loop controllers and the necessary wiring to connect the expert system to the process input/output interface. The process operating expertise contained in the knowledge base was provided by Wabush Mines personnel.

THE COMDALE/C REAL-TIME EXPERT SYSTEM

COMDALE/C is a development tool and system for creating *real-time* on-line supervisory control systems. A COMDALE/C application program will acquire data from a process, examine it in a fashion similar to the most experienced operators and then provide the operating personnel with:

- the goals of each process operation;
- the states of each process group;
- recommendations for corrective and control action.

Such systems can eventually be used to close the loop entirely, allowing COMDALE/C to initiate control actions directly by manipulating set points and final control elements. In this application COMDALE/C is used in the closed loop control mode.

The entire suite of modules in this package operate in a multi-tasking environment so that real-time decision-making is not interrupted by user queries or requests. Each module within COMDALE/C is a separate-independent

individually-executable task manager. The COMDALE/C modules are responsible for:

- _ Data acquisition and management
- _ Real-time expert reasoning
- _ Scheduling of events
- _ System health monitoring
- _ Interaction with human operators
- _ Explanation of activities
- _ Application configuration and maintenance

The system is open, allowing communication to take place on a single computer or across a network. COMDALE/C modules can be distributed to suit the needs of the users, information viewed in the Control Room can also be viewed in the Plant Manager's office. Users can query the system for advice about past, present and future conditions or control actions without interrupting the control activities of the system.

All displays are available to the Users through two User Interface modules - ProcessView and ExpertView. ProcessView can be configured to provide a mimic-board diagram of the process flowsheet and other dynamic process graphics. Multiple screens can be configured, and several screens displayed simultaneously in a windows environment. Multiple windows can be opened to view related process groups. The state of the process can be depicted on each window with buttons, icons, trend graphs and text objects. The user can adjust the values of set points and other changeable process variables through ProcessView.

ExpertView displays the thought process of the System as the process states change. Messages are sorted into different classes so that flotation operators for example, only see flotation class messages, while grinding operators only see grinding class messages. Through ExpertView, an operator can query an action taken by the system. A novice operator can ask the system to explain how information is used or how certain conclusions are made. This latter functionality provides an excellent training environment for new users.

Communication with the process is through the data acquisition and management modules. Each application may require specific communication software depending upon the plant instrumentation available. COMDALE/C can communicate with DCS systems as well as PLC-based control systems. A system can be installed initially to simply provide logging and interface capability without the need for expert advising and control. The expert system option can be implemented later without disrupting the operation of the installed system.

SYSTEM DEVELOPMENT

The project commenced with the development of an initial knowledge base at Comdale's office. The knowledge and expertise for the operation and control of Mill Line No. 4 was acquired through telephone and facsimile interaction with Wabush Mines chief metallurgist. The initial knowledge base provided insights into the grinding circuit control concepts used for decision making and their representation. An on-site visit of 5 days by Comdale personnel focused on the acquisition of detailed knowledge used to control Mill Line No. 4. The knowledge was acquired through interviews with Wabush Mines mill superintendent and the chief metallurgist. Major modifications were made to the initial knowledge base, in particular, the structure was changed. Off-line testing of the knowledge base was performed at Comdale's office, this consisted of using comdale's consultant expert system tool, COMDALE/X, to execute the knowledge base. The user entered the value of process variables as requested by COMDALE/X by means of questions on the computer screen. Entries were made by way of the keyboard. COMDALE/X provides various options for debugging the knowledge base; rule tracing, setting of rule breakpoints, cross-referencing, justification of conclusions, etc. Off-line testing of the knowledge base was aimed at verifying that the correct decisions were being made, that the correct reasons were being used to make those decisions; and to analyze the completeness of the knowledge base.

Development of the communication interface between the Foxboro 761 single loop Controllers and the expert system was done at Comdale's office. Configuration of the graphical screens and the various modules comprising the expert system was done in parallel with development of the communication interface. Graphics displays were configured to show time-varying trends of process variables, bar displays and instantaneous values of groups of variables. Also, screens showing faceplates for all 761 Controllers were configured, these faceplates allow access (by way of the computer keyboard) to the options on the 761 Controller panel - changing of setpoints, automatic/manual mode selection, etc.

The second on-site visit by Comdale personnel - of a week duration - was aimed at acquiring more expertise from Wabush Mines personnel with which to expand and refine the knowledge base. It was also intended to put the expert system on-line. Discussions with Wabush Mines milling circuit operators provided valuable insights and expertise relevant to controlling the process. The knowledge base was expanded and refined on-site. Fuzzy sets were defined for qualitative process concepts such as mill power-draw too

high, spiral density o.k., etc. The expert system was put on-line in a monitoring capacity, that is, process data was obtained from the 761 Controllers and used to make decisions but those decisions were not output to the plant. Instead, messages pertaining to the decisions made were printed to a computer screen. The aim of this exercise was to test the timeliness and correctness of the decisions been made by the expert system, and also to evaluate the communication between the controllers and the expert system. At the end of the visit the expert system was on-line monitoring, providing the control room operators with important graphical trends of process variables, their instantaneous values and access to the 761 Controllers on the plant floor by way of the computer.

Back at Comdale's office, telephone conversations with Wabush Mines personnel provided additional information to fine tune fuzzy sets and to establish time periods of observation of trended variables. Additional graphical screens were configured at the request of Wabush Mines. Wabush Mines personnel experienced problems with instability of the mode settings of the 761 Controllers as indicated by the faceplates (on the computer's screen). Difficulties were also experienced with starting the expert system after shut down. The former problems were related to the communication software and were corrected at Comdale's office. The latter problem was related to improper shut down of the expert system by the user. Changes were made to make the system more robust to withstand improper shut down. The graphical module was modified to accommodate average trends, and the knowledge base was modified so that trending information could be used for decision making.

The third and final on-site visit by Comdale personnel was aimed at putting the expert system on-line in a controlling capacity. This visit, of two weeks duration, occurred after all the necessary instrumentation was done by Wabush mines personnel. The initial phase of the visit focused on fine tuning the knowledge base and fuzzy sets, and modifying the various configuration files of the expert system modules. During the modification of the knowledge base and the configuration files, Wabush Mines personnel worked with Comdale personnel to gain an understanding of the system with a view to provide maintenance, modification and expansion of the system after it was commissioned.

The refined expert system was put on-line in a monitoring capacity, tested and debugged. Testing consisted of monitoring the messages output whenever a decision was made, examination of the rules responsible for those decisions and verifying the decisions and the rules (knowledge) with the operators. Putting the expert system

in a controlling mode (or a closed loop mode) essentially means changing the mode of the 761 Controllers from Panel to Workstation. Whenever a 761 Controller is in Panel mode the expert system is unable to output its decision (change in setpoint) to the Controller. Changes to the setpoint can only be made by way of the front panel on the Controller itself. The expert system is updated with all such changes. In order for the expert system to output its decision to the 761 Controller, the Controller has to be in Workstation mode. In this mode the Controller tries to maintain the variable at the setpoint determined by the expert system. The setpoint cannot be changed by way of the front panel on the 761 Controller. It should be noted that the mode of operation of a Controller is specific to that Controller, and is independent of, and has no effect on, the modes of other Controllers.

The expert system was put on-line in a controlling capacity after the evaluation of the expert system performance in an on-line monitoring capacity. This was done by putting the 761 Controller for the mill feedrate in Workstation mode; the other Controllers were set to Panel mode. Examination of the mill feedrate behavior in response to changes in the mill power-draw indicated that the expert system performance was excellent. The other 761 Controllers Panel mode settings were changed to Workstation and the expert system was in total control of Mill Line No. 4. The expert system was kept under constant surveillance over a 48 hour period and its performance evaluated. The on-line controlling performance of the expert system met with the approval of Wabush Mines personnel, and the system was commissioned.

The final expert system had the following components:

- _ 110 rules
- _ 35 fuzzy sets for recognition of process states (inputs)
- _ 19 fuzzy sets for control actions (outputs)
- _ 25 fuzzy sets to identify trends
- _ 24 variables monitored for time variation.

Sample rules are:

Sample 1:

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if
    mill powerdraw is high and trending upward fast
and
    recirculating density is not too high and not
    trending upward
and
    recirculating sump level is too high and trending
    upward
then
    reduce mill feed water by a small amount.
```

Sample 2:
 if
 mill powerdraw is critically high
 then
 reduce mill feedrate immediately.

HOW THE EXPERT SYSTEM WORKS

Sensors attached to various components of Mill Line No. 4 - mill feeder scale, mill motor, sumps, flow lines, etc. - return values of process variables to Foxboro 761 single loop controllers. A total of 9 Controllers are installed at various locations, and all are interconnected in a loop that terminates at a junction box in the Central Control Room. Each 761 Controller provides the necessary input/output functionality to convert the sensor readings into data that can be used by a computer. In addition to the input/output function of the 761 Controllers, they also provide PID loop control. The output of the 761 Controller is incompatible with the input of the project's computer. In order to achieve compatibility it was necessary to install appropriate hardware between the output of the 761 Controller and the computer's input. The hardware, a Foxboro RS-232/485 converter, was connected between the junction box (termination point for all sensor readings passing through the 761 Controllers) and the serial port input of the project computer. A Compaq 486 microcomputer with 16 Mega-bytes of RAM, 200 Mega-byte hard disk, Super VGA color monitor, and operating at 66MHz is the project computer located in the Central Control Room. The computer runs under the QNX operating system and contains the expert system software. The expert system consists of various computer programs, or modules, and each module has its own configuration file. Notable modules are the 761 Communication module, the Database, Controller and Graphical modules.

The 761 Communication module transmits the sensor values between the Foxboro 761 Controllers and the Database module. The Communication module is configured to distinguish each 761 Controller, its assigned process variables and PID loop. The Controller module uses the process values in the Database and the process knowledge in the knowledge base to make decisions -- mainly adjustment of setpoints. New values for setpoints are determined by the Controller module and put into the Database. The Communication module then outputs the new setpoint to the appropriate 761 Controller which uses it as the new setpoint for its PID loop. The Graphical module obtains the most recent values of process variables from the Database and displays those values according to how the module is configured, that is, trends, bar charts, etc. The expert

system is started by turning on the computer and typing the appropriate command on the command line. The 761 Controllers should be in Panel mode before the expert system is started. This prevents the expert system from controlling Mill Line No. 4 immediately on start-up. (About 15 minutes is required for information about trends to be established). After start-up the 761 Controllers are switched from panel mode to Workstation by the operator. The expert system will run continuously until it is stopped, on stopping it switches the 761 Controllers from Workstation mode to Panel. This returns control back to the actual faceplates.

The following are examples of messages that the process operator may receive during operation of the expert system.

Example 1:

Your mill feedrate was just increased because the recirculating load density is too low and the feedwater is at its minimum.

Example 2:

The power draw on the mill is too low and the recirculating sump level is too high. The feedwater is at its minimum value.

Monitor the situation for possible overflow of the recirculating sump.

Check for plugged pumps and grates.

Example 3:

The recirculating sump level is too high and recirculating load flowrate is too low. Check that the pump is working well and call maintenance if necessary.

RESULTS AND OBSERVATIONS

The start-up operation to put the system on-line was very smooth, there were no disruptions to the plant or process. The expert system performance has surpassed all expectations. The expert system strives to maintain a maximum mill feedrate which is set by the control room operator and simultaneously ensures that the circuit is operating within the safety constraints. The mill on Line No. 4 is operated at a maximum power draw of only 60% compared with 75% on the other mill lines. Despite the disadvantage, Mill Line No. 4 production performance is at least 20% better than the other mill lines especially when processing hard ore. In addition to increasing throughput, the expert system has reduced down-time caused by plugged pumps. The system has also improved spiral density control leading to improvement in product quality. The expert

system maintains optimum spiral feed density (25-30% solid) through pumpbox level adjustment, Figure 2, it also considers the ore feedrate, Figure 3.

Figure 4 shows the expert system maintaining higher throughput levels in comparison to standard operation when processing hard ore.

CONCLUSIONS

A fuzzy logic expert system for Iron Ore Processing was successfully implemented at Wabush Mines. The system was jointly developed by Wabush Mines and Comdale Technologies. The installed system improved production and productivity of Mill Line No. 4 (especially when hard ore is being processed), it was readily accepted by process operators. The expert system has been in continuous operation for four years. Based on the benefits and the high return on investments, the expert system was duplicated on a second mill line. Plans are in place to install expert systems on all mill lines.

ACKNOWLEDGEMENTS

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SPIRAL "A"

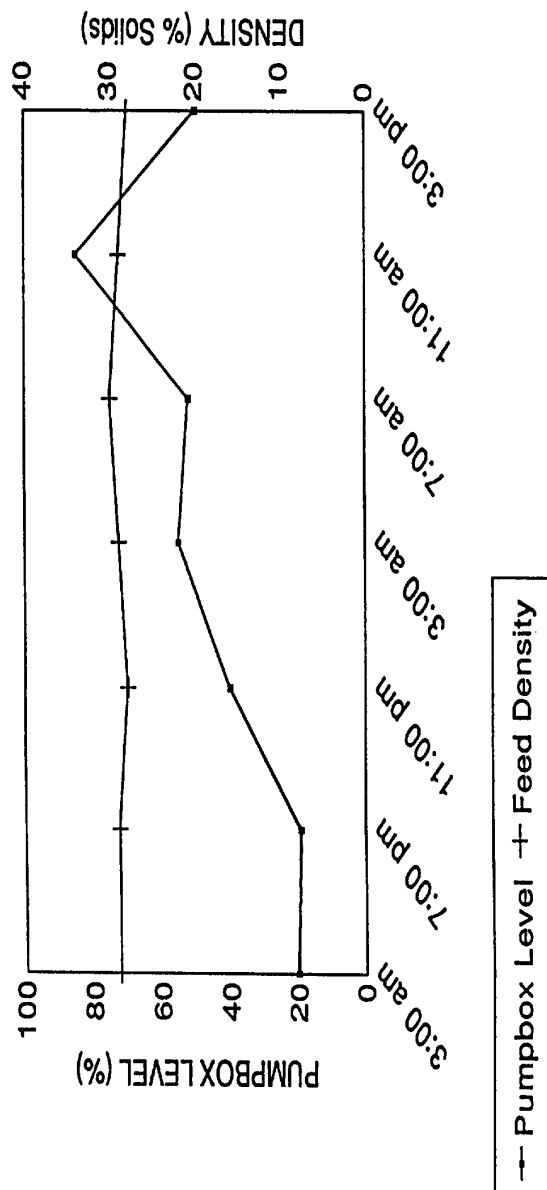


Fig 2. Constant Spiral Feed Density with Level Adjustment.

GRIND CONTROL EFFECT ON SPIRAL FEED DENSITY

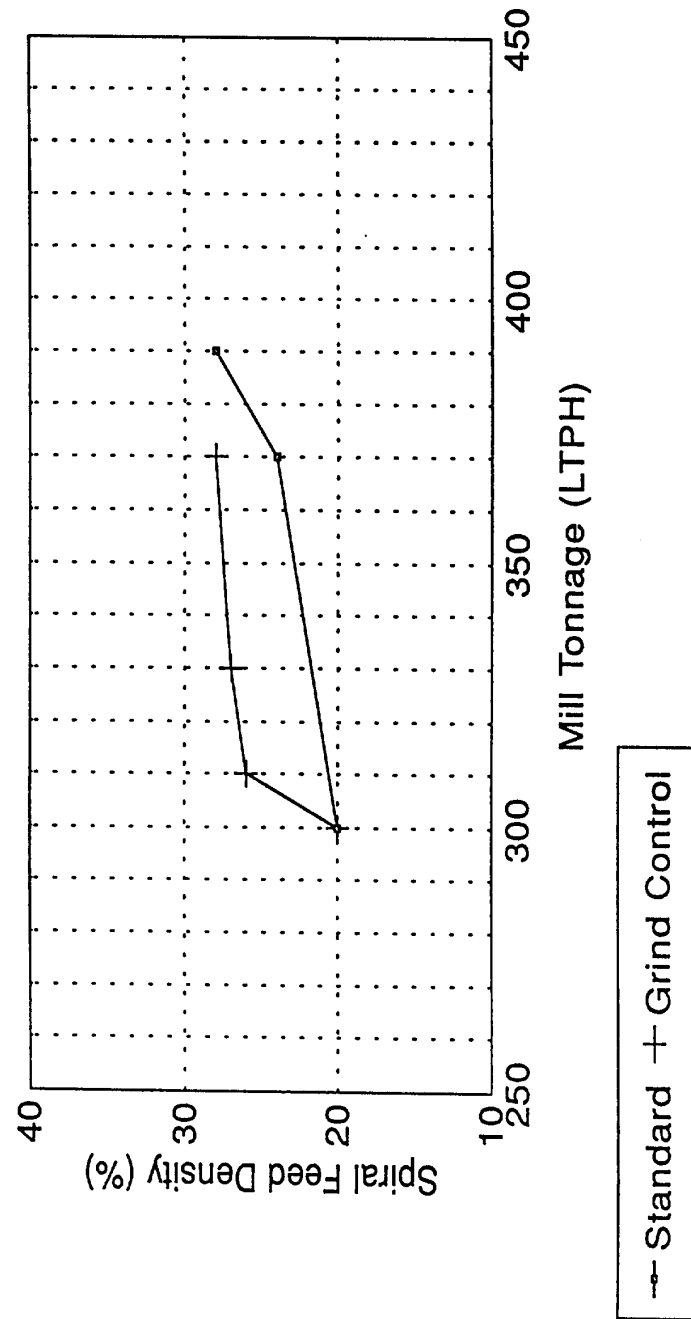


Fig 3. Spiral Feed Density Increase at Lower Tonnages.

MILL THROUGHPUT

WHEN PROCESSING "HARD" ORE

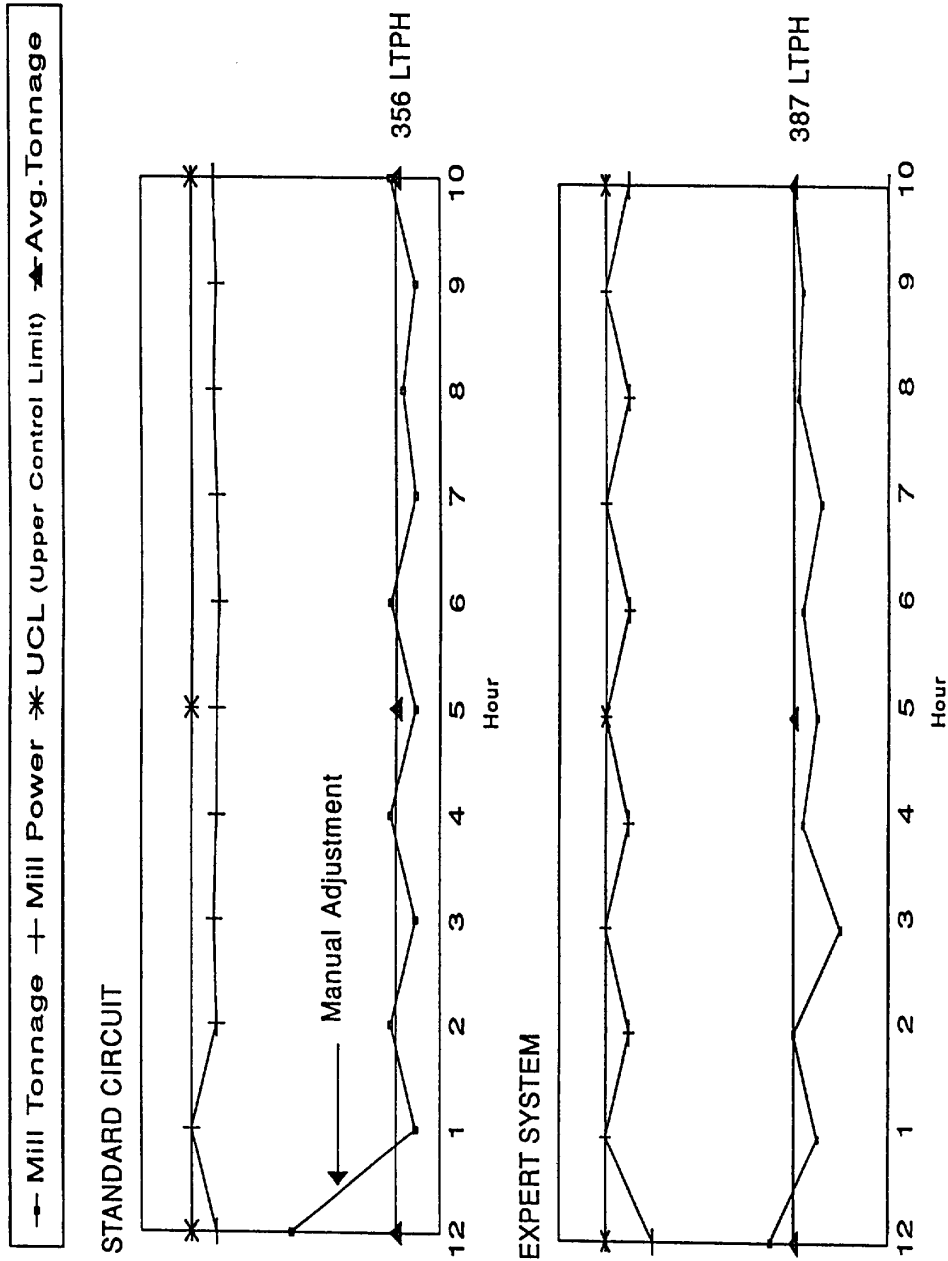


Fig 4. Expert System vs Manual Operation.