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Installation of an automated laboratory flotation column

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A thesis submitted to the Faculty of
Graduate Studies and Research
in partial fulfilment of the requirements of the degree of
Master of Engineering

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"I am the path, truth and life..."

Jesus of Nazareth

To professor **JACQUES DECUYPER**
Long years of teaching and helping to transfer technology to Latinamerica.

ABSTRACT

The installation of instruments and devices required to fully automate a laboratory flotation column, and the configuration of the software required to drive the column from a PC terminal was accomplished. Beside the normal Input/Output link required, and as an application, the system was configured to perform stabilizing level control through feedback control loops. Three parallel software control loops were built, manipulating, alternatively, the underflow, feed or washwater streams to control the level.

The level was calculated through the readings of up to three pressure transducers. Proportional, Proportional-Integral and Proportional-Integral-Derivative control were used in the feedback loops. In the process, problems related to the accuracy and range of valid level calculation, and to the use of washwater as the manipulated variable were identified. Some changes to current industrial practice are suggested in order to correct these problems.

RESUME

L'installation des instruments et dispositifs, ainsi comme la configuration du software requis en l'automatisation d'une colonne de flottation de laboratoire, et leur opération à travers d'une terminal de PC ont été accomplies. En plus du reliage entré/sortie nécessaire, et comme une application, le système a été configuré pour pouvoir exécuter contrôle stabilisateur du niveau par milieu d'une boucle retro-alimentée. Trois boucles en parallèle, qui alternativement, manipulent l'eau de lavage, l'alimentation et la courante inférieure furent construites au bout de contrôler le niveau.

Le niveau fut calculé par jusque'à trois transducteurs de pression. Contrôle Proportionnel, Proportionnel-Intégral et Proportionnel-Intégral-Dérivative, ont été utilisés dans la boucle retro-alimentée. Au cours du travail, problèmes en relation à la précision et au range de validité du calcul du niveau, ainsi qu'à l'utilisation d'eau du lavage comme variable manipulée furent identifiés. Quelques changements à la pratique industrielle courante de mesure et contrôle du niveau sont suggérées pour corriger ces problèmes.

Acknowledgements

The Master's is a program which I have been wishing to take since my graduation (long ago). Not just me but my whole family, to whom I must be thankful for literally pushing me to accomplish it.

Initially I wish to thank professor Laeeque Daneshment, of the Mining group, not only for accepting my application but for effectively guiding me in the selection of courses related to the field of instrumentation and control.

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To Dr Cesar (Pato) Gomez who at the beginning, was the only one sure I could do the work and who participated actively in most parts of the project. The reason for his help was simple, he knew a lot about instruments, I/O boards and a little bit about the software, and this experience, was generously shared during the installation of the system. In this regard thanks also go to Martin, Joe and Evgueny, who built and installed the column and solved many problems on the processing of signals and electronic connections.

To Dr. Rao, professor Laplante, professor Xu, and all the graduate students in the group for their friendship, support, and occasional advice.

To INCO (Sudbury), for permitting us to use their columns to collect pressure profile data and to CANMET (Ottawa), where an automated laboratory column based in paart on my work was installed, and where some tests were run. Finally I would like to thank the INCO-NSERC Chair in Mineral Processing, the MITEC-NSERC CRD grant and CANMET for funding the research project.

Jaime

LIST OF CONTENTS

GLOSSARY OF TERMS

C.V.,	Controlled variable.
DCS,	Decentralized control system.
E_n,	Error at present sampling time, (difference between calculated and set point level).
E_{n-1},	Errors at given previous sampling time.
F_n,	Feedback tag value.
h1, h2, h3	Position of taps of P1, P2 and P3 respectively, cm.
HA,	Historical Assign, FIX-DMACS program.
HC,	Historical Collection, FIX-DMACS program.
HD,	Historical Display, FIX-DMACS program.
Jf,	Feed flowrate, cm/s, see block FFT
Jg,	Gas flowrate, cm/s, see block AFT.
Ju,	Underflow flowrate, cm/s.
Jw,	Washwater flowrate, cm/s, see block WFT.
Kc,	Proportional controller constant.
(*)	(Kp in equation 4).
Kp,	Process gain,
LEV1,	Froth depth calculated using one pressure transducer, cm.
LEV2,	Froth depth calculated using 2 pressure transducers., cm.
LEV3,	Froth depth calculated using 3 pressure transducers, cm.
LSP,	Level set point
M.V.,	Manipulated variable.
P1, P2, P3,	Top, middle and bottom pressure, cm/s.
PB,	Proportional band.
S,	Slope at sigmoidal point.
T,	Sampling time (scanning time at which errors are calculated).

T_d,	Dead time (time delay).
Y_{n-1},	Output of controller in previous to current sampling time.
α,	Derivative mode filter.
β,	Proportional action constant.
γ,	Derivative action constant
Δy_n.	Increment of the PID output at current time.
ΔB	Change in controlled variable.
ΔA	Step change in manipulated variable.
ϵ	Controller error (calculated level and level set point difference)
(*)	(E_n in equation 4).
ϵ_g,	Gas holdup, see block GHU.
ρ_c,	Collection zone density.
ρ_f,	Froth zone density.
ρ_f (est.),	Estimated froth zone density
ρ_l,	Density of a given layer in the froth or slurry zone
τ,	Time constant
τ_d,	Derivative time constant or rate constant, minutes.
(*)	(Td in equation 4)
τ_i,	Integral time constant or reset time, minutes/repeat.
(*)	(Ti in equation 4)

<u>Notes</u>:

- A list of block tag names is presented in Appendix 1, page 91.
- (*) Terms in parenthesis are used exclusively in equation 4, section 4.3.2.

LIST OF FIGURES

LIST OF TABLES

LIST OF APPENDIXES

CHAPTER 1 - INTRODUCTION and LITERATURE REVIEW

1.1 Flotation

This mineral separation technique dates back to the turn of the century when it was discovered that mineral particles would selectively attach to air bubbles. Following this, there was extensive work on both the chemical (e.g. reagents to promote selectively) and mechanical (e.g. flotation machines) aspects of the process. This thesis is concerned with flotation machines and one device in particular, the flotation column (Figure 1).

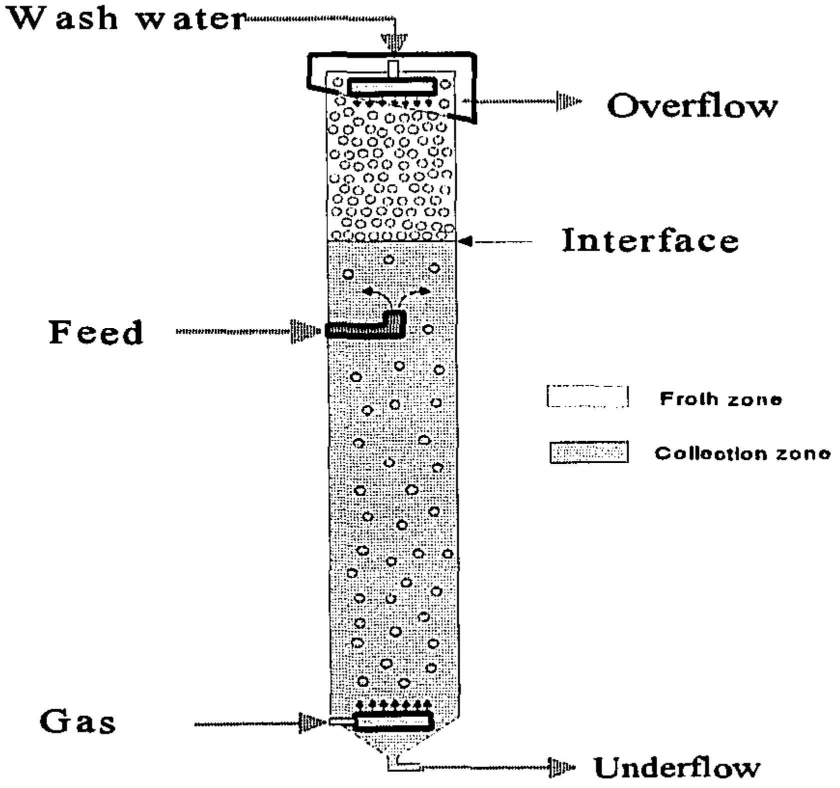


Figure 1. Schematic of a flotation column

Figure 1 shows a schematic diagram of the main elements of a flotation column. There are five fluid streams:

1. A liquid stream, wash water.
2. Three slurry streams, feed, underflow and froth overflow.
3. A gas stream, air.

Two zones have been characterized namely, the cleaning or froth zone and the collection or slurry zone. The interface between these two zones is variously referred to as the "level", "slurry level" or "froth depth". In this thesis level and froth depth are used interchangeably, and because it is current practice, the interface position is measured as the distance from the top of the column.

A well documented advantage of flotation columns over conventional mechanical cells, resides in improved rejection of hydrophilic (generally gangue) minerals through good control of the operating parameters, in particular the bias.

The **bias** is defined as the net flowrate of liquid crossing the interface (by convention, when this flow is downwards, it is a positive bias). Other parameters of importance are the **gas holdup** in the collection zone, and the **froth depth.**

Besides the obvious advantage of operating under steady conditions, high efficiency will be attained if the bias, gas holdup and froth depth are kept at optimum values. This condition can only be reached if accurate and reliable instruments and controllers are available and if a degree of automation is possible.

Industrial practice requires, at least, the ability to keep the froth depth at a given set point and to change it with minimum delay. This is only possible through reliable sensor and control systems.

At the laboratory scale, the need to obtain accurate data together with the necessity to collect and store large amounts of data, make manual procedures impractical. This provided the motivation to automate a laboratory column which is the objective of this thesis. Laboratory tests usually require information to be gathered under steady-state conditions. On the other hand, in many cases, information about the transient response, which requires fast data collection of many variables, is required. Both situations cannot be handled, unless an automated column is used.

1.2 Current froth depth control practice

Most of the published information refers to stabilizing control usually achieved through single feedback loops manipulating the wash water or the underflow. In the case of wash water, control is coupled either to a constant feed/tailings flowrate ratio or difference (i.e. bias)[6, 12].

Optimizing control is not yet widely implemented. Reports on optimizing control do not give a clear indication of any advantage over simple stabilizing control[2].

1.3 Interface detection methods.

To monitor the froth depth in a flotation column, both direct reading and indirect methods have been used:

Direct sensing methods detect the location of the collection/froth zone interface. An example is the ultrasonic detector, which uses the sonic reflection from the interface. However, operational problems limit its applicability. One kind of semi-direct method is the float, which exploits differences in density across the interface. These are accurate but subject to solids build-up[7].

The indirect methods, are less accurate because they rely on calculation. Two methods are the use of electrical conductivity[11] and pressure[5]. The pressure-based technique is quite common. Up to four pressure transducers send signals to a computer to calculate the interface position.

1.4 Froth depth detection using pressure.

The use of pressure has the attraction that, for a sensor placed below the interface, the level, in principle, is directly related to the hydrostatic pressure.

In practice, zone densities change in an unpredictable way due to fluctuations in solids and gas content. Consequently, the calculated and true level can be far apart. One resolution is to use multiple pressure transducers, in effect to provide on-line estimations of zone density. In flotation columns a common practice is to use three pressure transducers, two in the collection zone and one in the froth zone (Fig. 2). The general guidelines for positioning the three transducers are:

a) Place the bottom pressure transducer (P3) towards the bottom of the column, but away from the air injection point, to avoid disturbances.
b) Place the top transducer (P1), near the highest expected position of the interface.
c) Place the middle one (P2), close to the expected lowest position of the interface.

Unfortunately, the best feed inlet point to obtain the highest retention time, is also close to the lowest expected position of the interface. Placing P2 close to the feed inlet could generate disturbances and inaccuracies in the pressure readings.

Throughout this thesis, froth depth is either measured directly or calculated using the pressure method.

CHAPTER 2 - OBJECTIVES AND METHODOLOGY

2.1 Objectives of the project.

The general objective comprised three points:

- Build an automated laboratory column able to monitor, display and store data, performing all test manipulations through a PC terminal;
- Configure feedback control loops interfaced with the equipment in real-time;
- Demonstrate the ability to perform flotation tests with automatic froth depth control.

A more specific listing of objectives is:

a) Design computer screens (pictures and diagrams) to represent the process on-line;
b) Link elements of the control diagrams to the process elements in real-time using an I/O interface;
c) Allow operating conditions to be set through a PC control terminal;
d) Exert automatic control of the process according to a customer-configured strategy;
e) Display data generated in real-time, for monitoring and control uses;
f) Display historical data in the form of trend curves;
g) Store data in permanent files.

Points **b** and **c**, require an interface device capable of data exchange in real-time. All other points have to be accomplished by a software package or entered in a language compatible with the I/O device.

In Figure 2, the basic instruments and controllers required to operate a laboratory flotation column are presented:

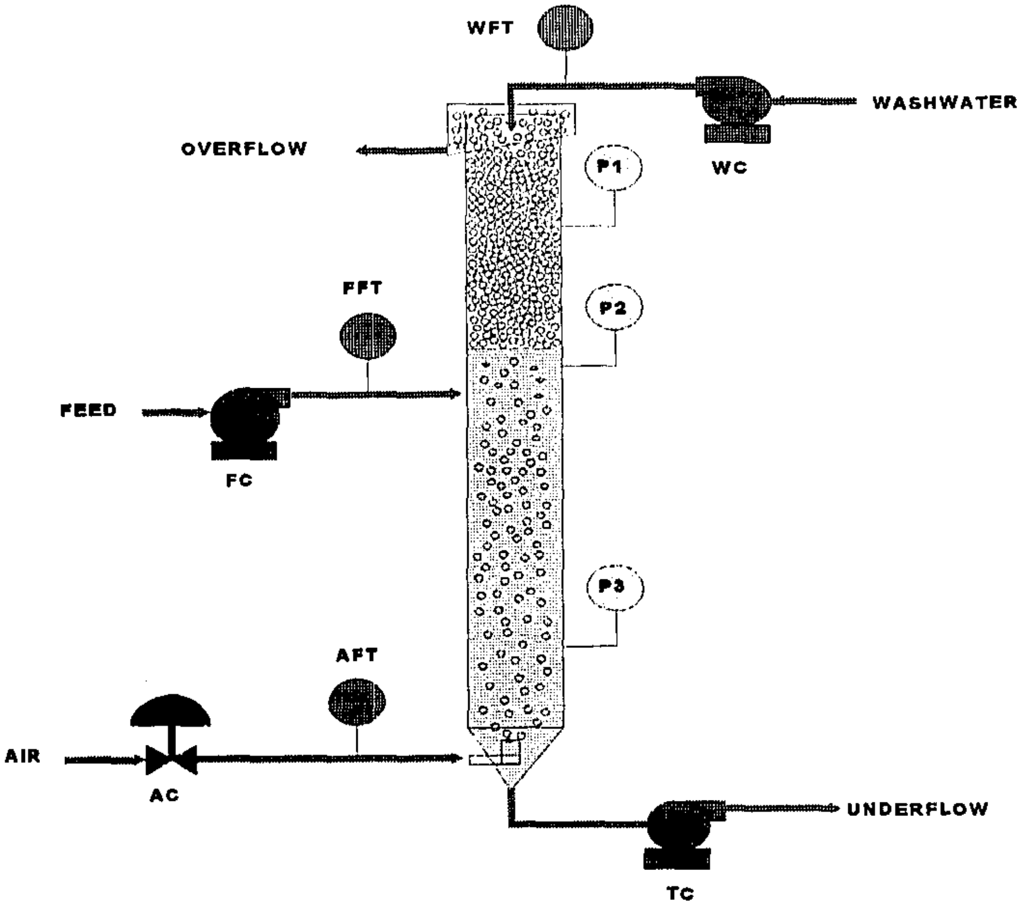


Figure 2. Location of sensors and controllers

2.2 Functionality

The sensors and controllers need to accomplish at least the following tasks:

- Measure the washwater (WFT) and feed (FFT) stream flowrates.
- Control the flowrate of the washwater, feed and underflow streams using pumps WC, FC and TC.

- Measure the air flowrate using gas flowmeter AFT.
- Control the air flowrate using control valve AC.
- Pressure transducers, P1, P2 and P3: Measure pressure as depicted in Figure 2. These values will be used to calculate the froth depth and gas holdup, in water/air systems.

2.3 Equipment selection.

2.3.1 Pumps

Three pumps to drive the feed, washwater and underflow, were required. These pumps had to be variable speed, and remotely controllable; a favourite for this task is the peristaltic model, which has the advantage of handling a large capacity range. The unit selected was the MASTERFLEX model L/P peristaltic pump, which is widely used in laboratory work. These were powered by 110 Volts alternating current, and are controlled through a 4 - 20 mA current signal.

2.3.2 Liquid Flowmeter

The selection of this instrument was difficult, because there is not much choice in the range required with output signals easy to manipulate. Finally, a turbine type meter (OMEGA, model FP - 2505) which gave 0 - 2 Volts DC pulse signals, was selected. This instrument can measure only clear liquid flowrate.

2.3.3 Air flowmeter/controller

Gas flowmeter and controller are available as single units, which greatly simplified the installation. The MKS model 5000, with a range 0 - 5 L/min, 0 - 5 Volts controller input signal and 0 - 5 Volts flowmeter output signal, was selected.

The main characteristic of this instrument is that it measures the gas mass and not volume, so that the gas volume reported is at standard conditions regardless of the counter pressure exerted by the system at the output of the meter.

2.3.4 Pressure transducers

Three BAILEY type PTSD differential Smart Pressure Transmitters were selected. These are used currently in industry, and are reported to give accurate, stable and reproducible measurements, reducing the burden of frequent recalibration. The meter has an internal microprocessor which allows the calibration and configuration of range according to the user's requirements. The output signal range is 4 - 20 mA.

2.3.5 I/O Device

As a requirement of the project was to build a system compatible with an existing one in Laval University (Québec City), and with another to be installed in CANMET (Ottawa), the selection of the **I/O device** and the **software** was restricted. For the interfacing device, the choice was between the boards produced by National Instruments, currently used at Laval University, and the **OPTO-22**, installed at CANMET. The group decision was to use the OPTO board as it appeared to be more flexible and compact, and required less signal conditioning (thereby avoiding incompatibility problems), reducing the time required to set-up the system.

A complete list of the equipment used on the column is presented in Table 1.

2.4. Description and components of the I/O device.

The OPTO-22 is an industrial I/O interface which contains in a single compact unit, analog boards or devices, digital boards, and power supply to drive boards and external signals. The quantity and type of devices must be specified by the customer (one of each in this case), as well as the voltage and total power required to drive the external signals. The complete set is supplied with a card to plug into an eight-bit wide slot in the PC to provide an extra serial port to link with the OPTO-22 trough an RS-422 dual pole cable. This card can be set to use any of the serial ports (COM1, COM2, COM3 or COM4).

Table 1. Equipment list

Units	Code	Description
3	P1, P2, P3	Bailey PTSD model, pressure transducers. 4-20 mA output.
3	FC, TC, WC	Feed, underflow, washwater. Masterflex I/P variable speed remote controllable, peristaltic pumps. 4 - 20 mA input.
1	AC, AFT	Air flowmeter/controller, MKS model 5000, Mass flow controller. 0 - 5 V input, 0 - 5 V output.
2	FFT, WFT	Feed, Washwater, Omega model FP 2505, turbine liquid flowmeter. 0 - 2 V pulse output.
1	OPTO-22	I/O interface device, complete unit, including power supplies and modules to condition and convert A/D and D/A signals to and from all instruments listed above.

The analog and digital devices have 16 connecting points, each point may be connected in parallel with specific instruments through specific modules. The modules condition and convert the input and output signals, from analog to digital or from digital to analog, respectively. The modules have to be specified according to the I/O function, and to the range and kind of signal to be converted, i.e. 0-5 V, 4-20 mA, pulses, and so on.

The speed of communication is relatively high, up to 19,200 bytes/s. The board can easily handle the requirements.

2.5 Software selection

Both the mineral processing laboratory at Laval University and CANMET in Ottawa were already using the package **FIX-DMACS**, created by Intellution, with specific application to process control. For compatibility the same package was used.

2.5.1 Software description, FIX-DMACS type MMI, version 3.0

The selected FIX-DMACS package is a "medium size" industrial software for automatic control purpose, which is capable of driving most I/O devices, including the OPTO-22 board. It is available in two platforms: DOS and WINDOWS, requiring a PC IBM compatible, model 486 with at least 8 MB RAM memory and 20 MB hard disk capacity.

The package cannot be run unless a hardware key is inserted in the parallel port LPT1. This is a limitation which impedes using the system for different terminals simultaneously. Another limitation is that the data exchange with the I/O device cannot be faster than one cycle per two seconds.

The software consists of a set of programs which can perform several tasks, which will be described next.

2.5.2 Draw

This is a drawing program used to design a schematic representation of the process, creating picture elements called "objects" which can be linked with blocks created in the database, in order to display current data values, or to write values to a given block using the keyboard.

The objects may have dynamic properties changing in colour and size according to the value of the linked block. It is also possible to create pushbuttons which, when activated, can perform some tasks or programming sequences using a set of commands provided in the Command Language editor.

2.5.3 Database builder

This is used to create a database in which blocks with specific names called "tags" are assigned to the first cell of a given row, then the information of each block is completed by specifying: type of block, address corresponding to the point selected for this block in the I/O device, type of device, range and units, degree of filtering, description, scanning time, initial mode, initial value, tag of the next block (if in a chain), and other information according to the type of block . Doing this the block is linked to a specific external instrument, to read or write data, or if it is a secondary block modify, condition or delay the signal of the previous block. More information about blocks will be given later.

2.5.4 View

This program acts as the man-machine interface, by means of the display and the keyboard. One can retrieve and operate using any layout created by *Draw*, but only one picture and one database can be active at a given moment. When *View* is open, the link with the instruments becomes alive, and one can read and write from and to the meters and controllers.

2.5.5 Historical assign, historical collection and historical display

These are independent programs used to define which blocks (variables) will be collected, the frequency of collection, scales to be used, and display format. Using these programs one can define how the permanent data files will be saved. "*Historical assign*" defines what information and with what frequency the temporary files will be saved in the hard disk; these files are automatically deleted from memory after a customer-defined length of time. Permanent files can be saved as listings of ASCII data or can be exported to ***Excel*** (version 4 or newer) in the form of a spreadsheet using the ***DDE*** (direct data exchange) utility program.

2.5.6 System configuration

This is a short program used to define the addresses and names of the devices, and to assign input or output function to each of the 16 points in each device. In this program, one or more configuration files are created, and a name is given to the **node** or terminal. The system uses only one configuration file at a time, which is loaded by default each time FIX-DMACS is run.

2.5.7 Type of blocks

The blocks created with the database builder are classified as primary or secondary blocks. A brief description of these block types follows.

Primary Blocks are used to link the database with the external instruments. These should be specified as **Input** or **Output** blocks. The main characteristic of these blocks is that they are assigned a specific address, which must correspond to the point assigned in the I/O board to the instrument. For this block the type of I/O device must be specified .

Scanning time is only stated for the input blocks.

Secondary Blocks are used to manipulate the information collected by the primary blocks, before being displayed on the monitor, or to perform some action and/or modification of the data before sending the values to the output blocks. In the present case, the main operation to be performed by the system is to create feedback loops for control purposes. In this group are: **Calculation, Programming, Ramp, PID, fanout, switch selector, event action,** and other types. The format used to specify mathematical operations, logic relation and programming steps are more or less standard. The software provides specific commands to be used in program blocks, and in pushbuttons. These are defined in the Command language list.

2.5.8 Simulated Driver

In some cases it is required to use virtual input or output blocks. In this event a simulated driver is used. With this modality, some objects can be created on the screen which may report some conditions of the process to be used by the operator, avoiding the necessity to physically install instrument to display or alarm under certain conditions. This simulated driver can also be used to create virtual chains which can perform calculations, or other tasks with no need to use a specific real channel, which should be used preferably with external instruments.

2.6. Complete automated column system

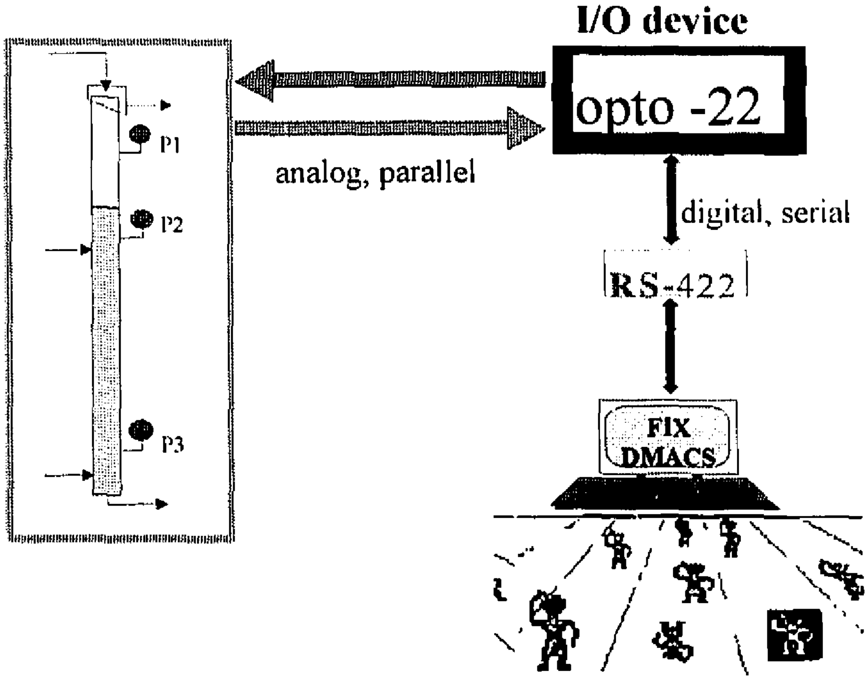


Figure 3. Schematic of the automated column system

Figure 3, shows the complete system installed in the column flotation lab, with the help of the mechanical and electronic staff of our section: Mr Martin Knoepfel, Joe Boka and Evgueni Chnyrenkov.

CHAPTER 3 - SYSTEM INSTALLATION AND CONFIGURATION

The system was setup according to the scheme presented in Figure 3 .

3.1 Procedure

To build the automated column the following steps were executed:

1. Instruments and I/O device installed;
2. Communication established with the PC, using a program supplied by Transduction, to first verify communication with the Digital and Analog devices, and then with specific points connected to external instruments;
3. Created in ***draw*** (FIX-DMACS), files necessary to represent the process and link the equipment and instruments to the monitor and control terminal;
4. Verified communication between the control terminal and the equipment, ability to read and write data via the monitor and keyboard;
5. Files created to display data in real-time, and to collect and store data in permanent files;
6. Block chains built to process the data to operate the column manually;
7. Controllability tested and PID parameters calculated;
8. Feedback level control loops and block chains created to enable alternatively manual and automatic operation;
9. Options added on the control panel for start-up and shutdown of the system.

3.2 Instrument installation

The power supply, to drive boards and instruments are installed inside the I/O device box. As the distance from the board to the instruments and to the computer is relatively short, no longer than 6 m, the environment is such that virtually no noise affected the signals.

The only delicate signal was the pulse generated by the turbine liquid meters, which required special shielded cables and connectors.

To connect the I/O device, any of the series port (COM1 to COM4) may be used, but due to a limitation of the software, a restriction was to use port COM1 or COM2 (but not COM3 nor COM4); COM2 was chosen to link the computer with the I/O board while COM1 used the mouse. At CANMET port COM1 is used to link with the I/O board, because the mouse used COM2.

During the installation of the hardware, the following problems were faced:

1. The link between COM2 serial port and the I/O device could not be achieved until this port was freed by a technician of the PC distribution company. The computers are sold configured with this port dedicated to another board.

2. The flowrate meters for the washwater and feed streams were not compatible with the rate modules of the analog device (OPTO-22), because of being slightly out of range. This was solved by the electronics technician, E.Chnyrenkov, who built three small signal adaptors, mounted directly on top of the rate modules.

3. Another minor problem was inappropriate shielding of the turbine meter connection, which generated a weak signal. This was solved using shielded cables and plugs.

3.3 Points distribution and modules installed in the I/O device

A point distribution map of the analog and digital brains, is presented next.

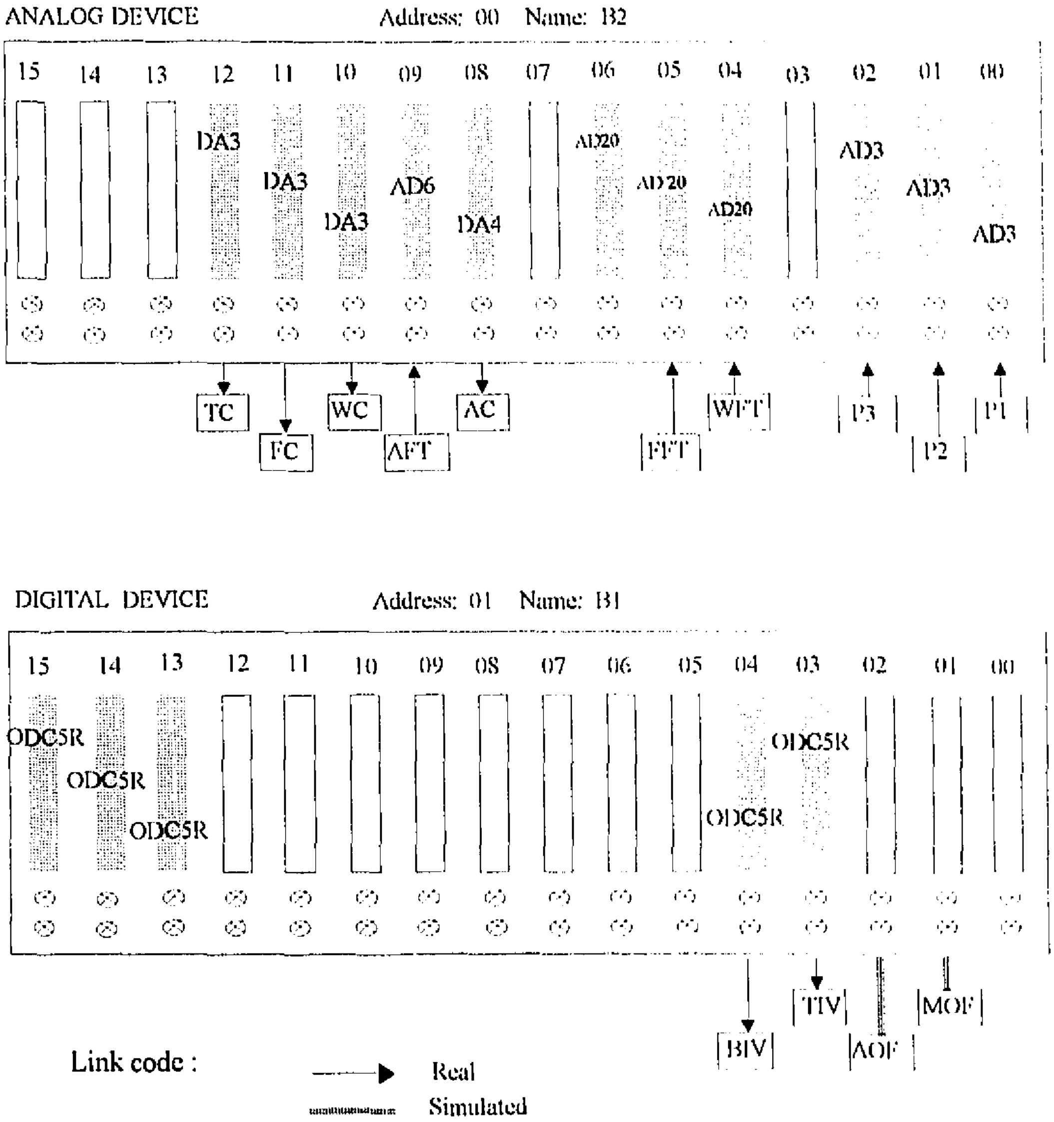


Figure 4. I/O Device, points and modules installation detail

A detailed list of modules and their characteristics is given in Table 2.

Table 2. List of modules installed in the I/O Device

Module	Characteristics	Address	Block's tag
AD3	A/D Analog input, 4 - 20 mA	B2:00	P1
AD3	A/D Analog input, 4 - 20 mA	B2:01	P2
AD3	A/D Analog input, 4 - 20 mA	B2:02	P3
AD20	A/D Analog input, Rate	B2:04	WFT
AD20	A/D Analog input, Rate	B2:05	FFT
AD20	A/D Analog input, Rate	B2:06	Free
DA4	D/A Analog output, 0 - 5 Volts	B2:08	AC
AD6	A/D Analog input, 0 - 5 Volts	B2:09	FT
DA3	D/A Analog output, 4 - 20 mA	B2:10	WC
DA3	D/A Analog output, 4 - 20 mA	B2:11	FC
DA3	D/A Analog output, 4 - 20 mA	B2:12	TC
----	no module required	B1:01	MOF
----	no module required	B1:02	AOF
ODC5R	Digital output, switch 120 V 50 W	B1:03	TIV
ODC5R	Digital output, switch 120 V 50 W	B1:04	BIV
ODC5R	Digital output, switch 120 V 50 W	B1:13	Free
ODC5R	Digital output, switch 120 V 50 W	B1:14	Free
ODC5R	Digital output, switch 120 V 50 W	B1:15	Free

3.4 Software configuration

The only problem related to the installation of the software, was due to an error in one diskette of the package. The OPTO-22 driver program corresponded to the ***MS-DOS*** version instead of the ***windows*** based version (which was supposed to be delivered).

Intelution sent a new diskette with the right driver version.

In configuring the software, many files are created, and stored in the directory named ***WINMMI.*** A listing of subdirectories and files, is given next:

```
WINMMI
|
|---- PIC         --------------------------------------------------------------► automop.odf
|---- LOCAL       -----------------------------------------------► auto.bat       canmet2.odf
|---- HTR         --------------------------------► chart.hgp      auto.scu       default.lyt
|---- PDB         ----------------► auto.pdb        htc.cfg        dbb.cfg        digos.odf
|---- HTRDATA     --► fixcom1.htc   manual.pdb      htrevnt.dat    default.fmt    flowrate.odf
└---- NLS         --► default.eov   autocan.pdb     htrgrp01.dat   fixcom1.dsq    jaime.lyt
                                    autowash.pdb    htrgrp02.dat   fixcom1.dtg    jaime.sbl
                                    fixcom1.op2     htrgrp03.dat   fixcom1.vsp    manualop.odf
                                    fixcom1.tag     pen.hgp        jaime.fmt      pressure.odf
                                                    time.hgp       manual.bat     valves.odf
                                                                   manual.scu
```

3.4.1 System configuration

This is a short program to define the addresses and names of the I/O devices, and to assign input or output functions to each of the 16 points in each device. Using this program one or more configuration files may be created, and a **node** name is defined for the terminal. The system uses only one configuration file, which is loaded by default each time FIX-DMACS is run.

To facilitate the exchange of layouts and setups, the same node name (***Fixcom1***) is assigned to the terminals in our lab and in CANMET. However, if in the future a direct link between terminals is intended, different names should be used.

The name of the default configuration file used in both labs, is ***auto.scu;*** however, the file used at CANMET differs from the file used at McGill due to the difference in hardware address assigned to the digital and analog boards. Another important difference is that at CANMET one analog and two digital boards have been installed, while at McGill there is only one of each. Total compatibility is not possible because of the different instruments used, and difference in column size and in pressure transducer positions.

The configuration files are stored in the directory ***local,*** path *c:\WINMMI\local,* under the names ***auto.bat*** and ***auto.scu***, and in the same directory three files*:* ***fixcom1.dsq, fixcom1.dtg*** and ***fixcom1.vsp*** are created when the node name is specified.

The configuration file specifies or defines the following information:

- The I/O driver to be used, **op2** in this case;
- The device name, **B1**(digital) and **B2**(analog);
- Each of the 16 points per device as **input** or **output** points;
- The serial port to be used in the communication: **COM2**;
- The address of each brain in HEX ; and lastly,
- The database name, **auto**, to be used as default each time FIX-DMACS is run in the terminal.

3.4.2 Database

The database created to link and process the information was saved under the name ***auto.pdb***, and stored in the subdirectory **pdb**. Figure 5 represents how the data is processed using different blocks linked in chains. In this figure, the names or **tags** of each block. are given.

The control strategy was defined in the *auto.pdb* database. It consisted of three feedback control loops to be used alternatively (not simultaneously), so that the operator can choose to control the level either by manipulation of the underflow, the feed or the washwater streams. In order to simplify the operation and, when necessary, to switch from manual to automatic operation, the mouse can be clicked on the corresponding program pushbutton (Figure 6), so the program linked to that pushbutton will sequentially execute a series of steps to deactivate a given loop and activate another one as required.

Another characteristic of the data processing is that the level set point, when in automatic mode, will set simultaneously all three software **PID's**, therefore it is unnecessary to reset the desired froth depth each time one switches from one control loop to another, in

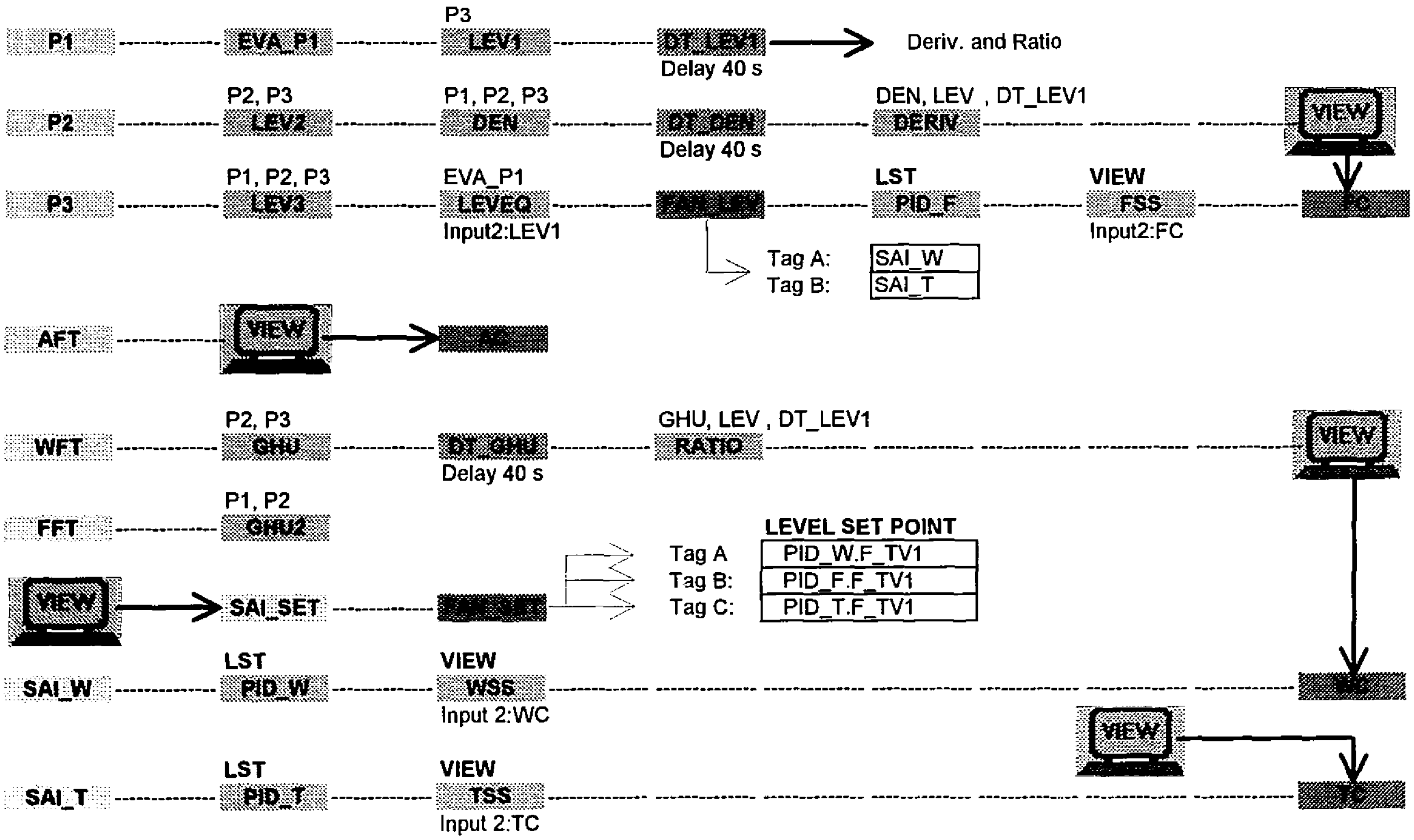


Figure 5.- Block chains in database AUTO.pdb

automatic mode.

The simulated driver was used to create virtual input points or blocks like: **SAI_SET, SAI_W** and **SAI_T.** These blocks were used in the chains to simultaneously set the level point to the PID blocks, and also to simultaneously input the calculated level to the PID blocks. This was necessary due to restrictions in the application of the **fanout** blocks, which use a single input to feed simultaneously two or more blocks.

At the time of building this particular application, the system was found to be unable to handle more than 64 Kbytes per database; however, it was possible to create parallel databases which can be alternately loaded when different data processing is required.

A listing of the blocks used in the database chains as well as the entries written in each block in order to perform calculations, run programs, select inputs, fanout outputs, define units, range of operation, and so on, is presented in Appendix 1.

3.4.3 Draw files

During the development of the system, the program **draw** was used to create different plots and diagrams representing the system on the screen. As a result, a series of picture files were saved under the subdirectory **PIC,** (path c:\WINMMI\PIC). These files can be identified by the extension **odf**.

The file ***automop.odf*** corresponds to the schematic representation of the flotation column, including all the instruments and equipment involved in its operation. In this diagram (Figure 6) are included some windows to display data, or state process conditions. A brief description about this diagram is presented in the next paragraph.

3.4.4. Graphic layout - process representation on the monitor

The screen layout, created to represent, monitor, and control the process is shown in Figure 6. In this Figure, the red arrows are the incoming and outgoing streams, grey circles represent transmitters (for flow or pressure transducers), and the yellow rectangles are input

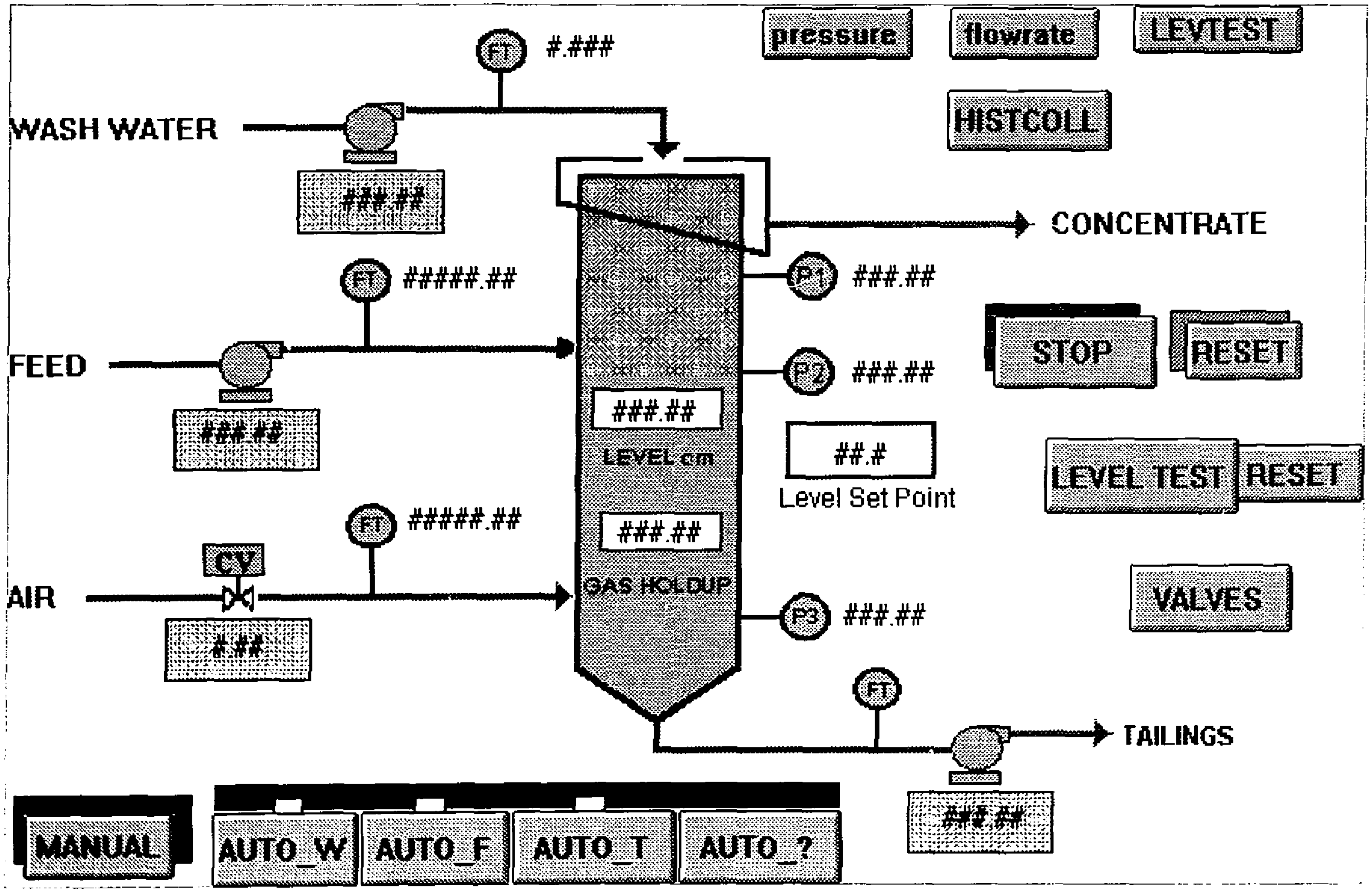


Figure 6 Process Monitoring and Control Layout, Automop.odf

points to set the pumps or the air controller. The grey rectangles are pushbuttons which can execute other tasks like: open a picture, or execute a short customer-defined program. A special object is the white rectangle in a blue frame, which is the input window for the level set point.

A listing of the function and action of each element in the monitoring and control screen, corresponding to the picture saved as *automop.odf*, is presented in Appendix 2.

3.4.5 Historical data display and storage

To select which data one needs to collect and the modality of collection, with the purpose of displaying or storing in permanent files, it is necessary to run the program **HA** (historical assign) and fill the information requested by means of a dialogue box. First one has to specify the tag name of the blocks which current values are to be collected, and second, with what frequency one needs to collect them. Then, the blocks are grouped accordingly to the frequency of collection (or sampling time).

One also has to specify how the data will be sampled. The sampling options are: Highest value, lowest value, average and last value. The files created with this program have the extension ***dat***, and are stored in the subdirectory **HTR**.

To collect data it is necessary to open or run the program **HC** (historical collection). When HC is running, the data is automatically collected and stored following the specifications made in the HA program. It is also possible to display, in the form of historical trend curves, the data corresponding to the blocks specified in the HA program, by running the program **HD** (historical display). In this program one can state the range, the span in time, the variables or blocks to be included, and the format of the plots to be displayed.

The data stored by HC, in the subdirectory **htrdata**, remains there for a lapse in time determined by the user (7 days in this case); after this period the files are automatically erased. The data can be saved in permanent files and exported it in the form of ASCII files (which may be read in any word processor program), or to **EXCEL**, in the form of a spreadsheet. A restriction is that the excel version should be **4.0** or more recent.

3.5 Functionality

How the system works, is discussed in this section. The steps to follow and the actions executed by the system are presented next:

1.- With the terminal running in **windows**, open FIX-DMACS. The I/O link is then activated, which is confirmed by the flashing of the led indicators in the serial communication board installed in the computer (fourth slot, rear of main PC frame). In the system here this flashing occurs every two seconds (scanning time).

2.- The man/machine interface, is activated by clicking the icon representing the ***view*** program in the FIX-DMACS group of directories. The layout (screen setting) and database defaults take over the settings of the linked instruments, and display current data in the graphical representation of the process on the screen. The system is set to run initially in **manual** mode, the indicating rectangle behind the manual pushbutton (**Mode_M**) is red, while the bar above the automatic operation mode pushbuttons is invisible.

3.- One can continue manipulating the different variables of the column, setting the pumps speed to fill the column. Another option is to click the **start** pushbutton, which will produce a sequence of steps to fill the column automatically.

4.- Finally if desired, when the column is filled above h2 (tap of P2, Figure 12, page 36), a switch to automatic mode can be made, choosing any of the options: **Auto_T**, **Auto_F** or **Auto_W**, which will change the active feedback loop, to control the froth depth through the selected manipulated variable (tailings, feed or washwater respectively), to stabilize the calculated froth depth at the value fixed by the level set point (LSP).

5.- The collection of historical data may be started at any time, by minimizing or exiting from ***view***, and running **HC** (clicking its icon in the FIX-DMACS group of directories); or by directly clicking the **HISTCOLL** pushbutton on *view* (Figure 6).

6.- In order to display the data in the form of trend plots, the **HD** program is opened, and a designated format retrieved, or a new display is created using a simple dialogue box. The HD program can display data collected previously and which are still recorded in the

HTRDATA directory. Data can be displayed in "frozen" format or displayed in real-time, updating the graphs each minute or slower, as specified.

3.6 ASCII permanent files, saving to EXCEL

There are two ways to create permanent files, one is saving as ASCII files using the **export** command in the HD program -in this case the files will have the extension ***dat***, and a name given by the user. These files will be stored in the HTR directory.

The second way is to export data to Excel. In order to do this, it is necessary to open and display data in HD, save the current display, open the **DDE** (direct data exchange) program from the FIX-DMACS group directory, minimize but keep DDE running, then open **Excel**, call the **Report** command from the menu, and create historical data link filling the dialogue box displayed on the screen. After creating the links, the data are transcribed by running the built-in macro coded under the combined key: < **ctrl-H**> which creates a standard excel spreadsheet, that may be saved as a current excel file. An important feature is that the **report** command is created in the excel **menu**, only if FIX-DMACS is setup in the computer after or over an existing Excel program.

CHAPTER 4 - LEVEL CONTROL APPLICATION

Once the system was complete, the communication between the PC and the instruments via the I/O device was tested (write and read to/from instruments), then the necessary elements and chains of blocks were created in the *auto.pdb* database to be able to calculate and control the froth depth.

4.1. Instrument response and manual controllability

A few initial test were run in order collect data related to the speed of response of the instruments, to calibrate them, and determine the stability and manual controllability of the process, as recommended by many specialists[9].

4.1.1 Response curves and calibration of instruments

Some initial tests were run to determine the stability, accuracy and repeatability of the readings of the following elements: pressure transducers, flowmeters, pumps and air controller.

4.1.1.1 Pressure transducers

Over the range and conditions of operation of the column, the accuracy of the pressure readings was good, giving practically no error for the top and middle pressure transducers. Only a slight error of ~ **0.15 %** was measured in the bottom transducer.

Some care must be taken to eliminate air from accumulating in the connecting hose (from the tap on the column to the instrument). This is particularly important for the top gauge. Failure to do so can cause appreciable errors in the pressure readings.

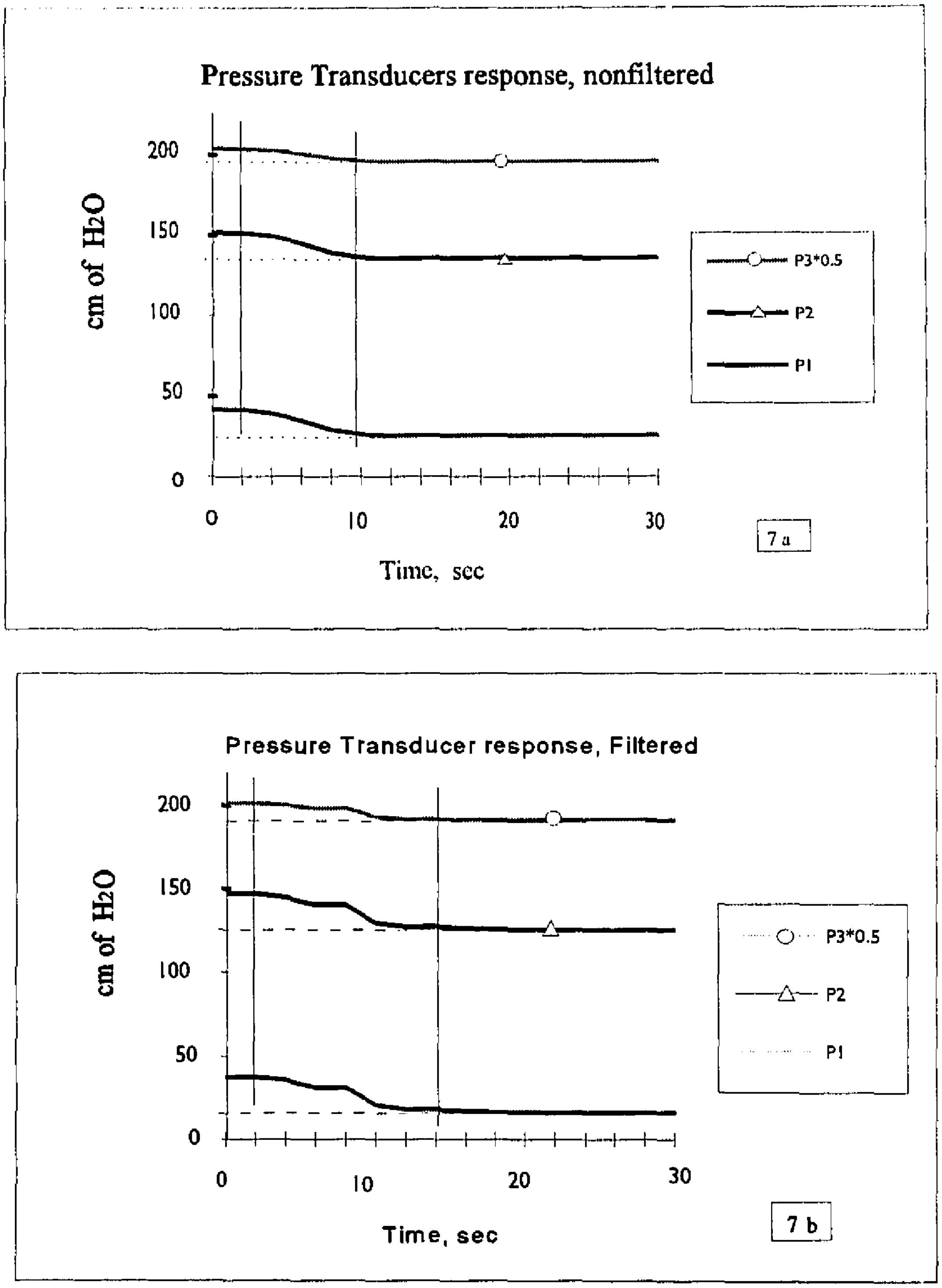


Figure 7. Pressure transducers response

The two sets of curves presented in Figures 7a and 7b, include two vertical lines to mark the initial response of the slowest transducers, and the final response for the slowest transducer, when it reaches 95 % of the total change. This percentage was selected based on the calculated froth depth using the pressure readings. The calculated froth depth at this point (95%) will give a maximum difference of ~ 2 cm, compared with making the final change 100%: this difference is equal to the deadband of the controller action.

Figure 7a shows the response of the three pressure transducers installed in a 3" (7.6 cm) dia. column, to a step in level, when the column was filled with tap water. The step was produced by a sudden opening of a drain valve (~ 5 seconds), to produce a fast change in level. It can be seen that the response presents a maximum delay of two seconds at the end of the step, and virtually zero delay at the beginning of the step. This is a quite fast response which can produce an acceptable tracking of level changes, and may allow for fast corrective action of the controller.

Something to be aware of is that the filtering option for the analog input blocks in the database of FIX-DMACS, may introduce significant time delays in the readings of instruments linked to these blocks, as shown in Figure 7 b. In this plot, a delay of ~ 5 seconds is produced, for a 7 point filter action (over 15 points of total filtering range). Low software filter action or none at all is recommended to avoid these software-provoked delays.

In relation to the linearity of readings, no distortion was detected. During the time elapsed in the execution of this project, it was not necessary to recalibrate the pressure transducers. This was not the case with the original gauges installed in the column[1], which required frequent recalibration (often at the beginning of each test).

4.1.1.2 Pumps and Flowmeters

Pumps and flowmeters were tested and calibrated together, by measuring the flow delivered at specific signal settings to the pumps in the range 4 - 20 mA. The calibration curves are presented in Figure 8.

As can be seen, the calibration curves for neither pumps nor flowmeters are perfectly linear, which introduces some error in the reported flowrate particularly for the intermediate

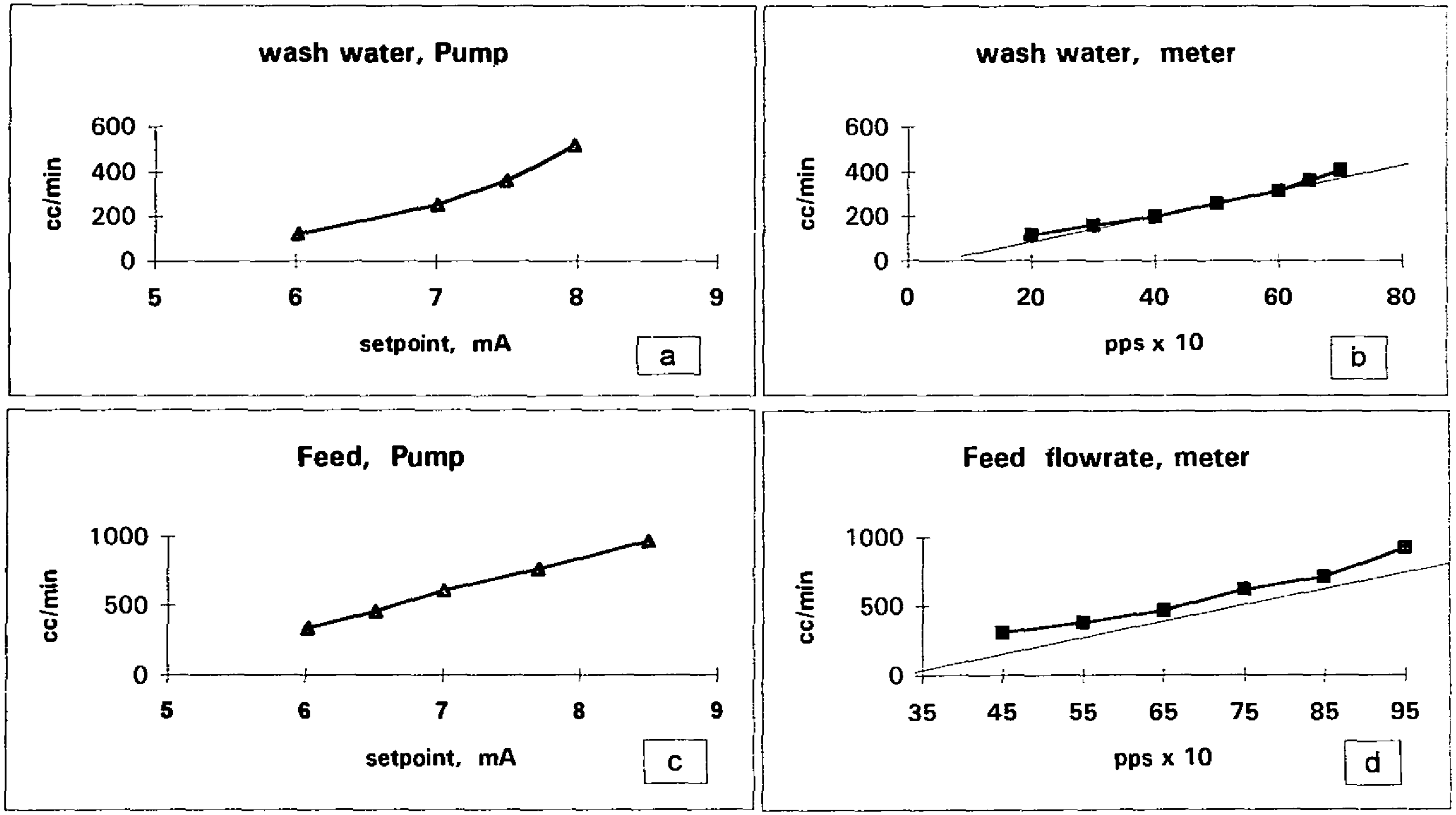


Figure 8. Calibration curves - McGill Column

flow range between points of calibration. However, good repeatability was verified for the flowmeters. In case of the pumps, naturally, they deliver different flowrates for the same setting, depending on the hydrostatic feed and output heads, friction in the lines and time effects on temperature and viscosity. This problem is unimportant for tests lasting ~ 2 hours, but becomes a problem in tests of longer duration.

The pumps are the slowest elements in the system. Even though they appear not to have a dead time their action is mechanically damped, and the flowrate reaches its final value in about 5 seconds. The flowrate is virtually unaffected by the hydrostatic head, and even for the underflow pump, which is the only one subject to a relatively large change in hydrostatic head (level changes are in the order of 2 m), the flowrate changes in ~ 3 units in the second decimal expressed in cm/s, for a given set-point on the pump.

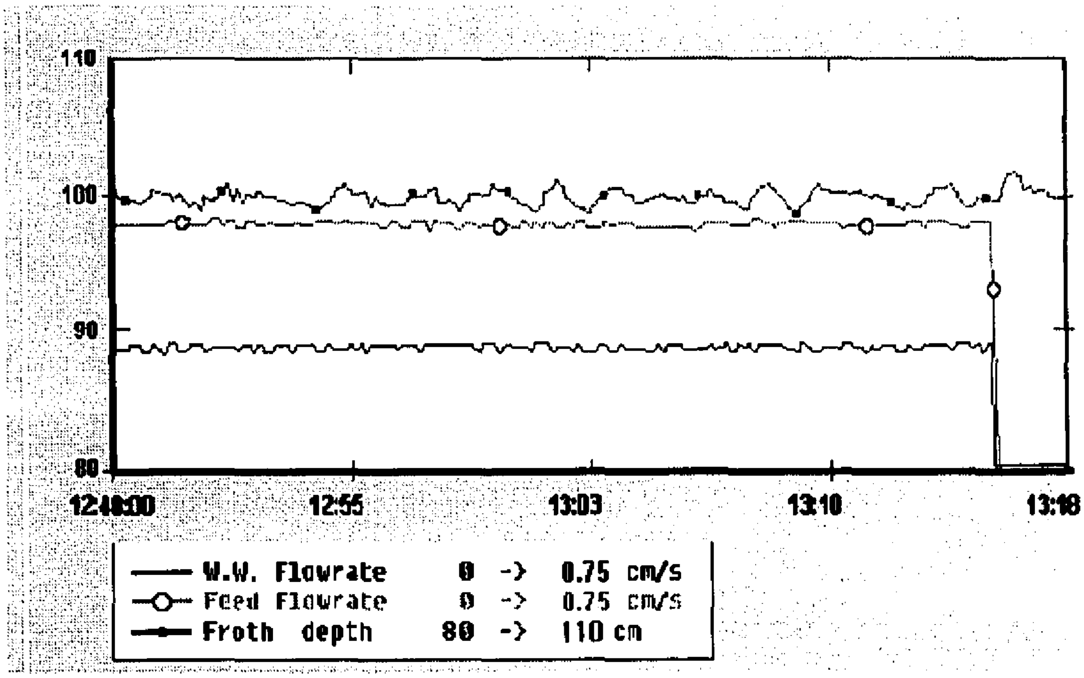


Figure 9. Feed and washwater flowmeters, stability test.

<u>Note</u>: In figures 9 and 10, the marks on the lines are identifiers, not data points.

Stability in the flowrate delivered by the pumps, and in the readings of the flowmeters are demonstrated in Figure 9. In this test, it can be appreciated that virtually no flowrate change was produced over ~ 1 hour: The pumps were set to fixed values.

The flowmeters being used monitored the washwater and the feed, but could not be used on the underflow stream, because tiny air bubbles pass through the filter and accumulate in the body of the flowmeter, eventually producing a drop in the values reported by the meter: these drops have the shape of peaks, as seen in Figure 10.

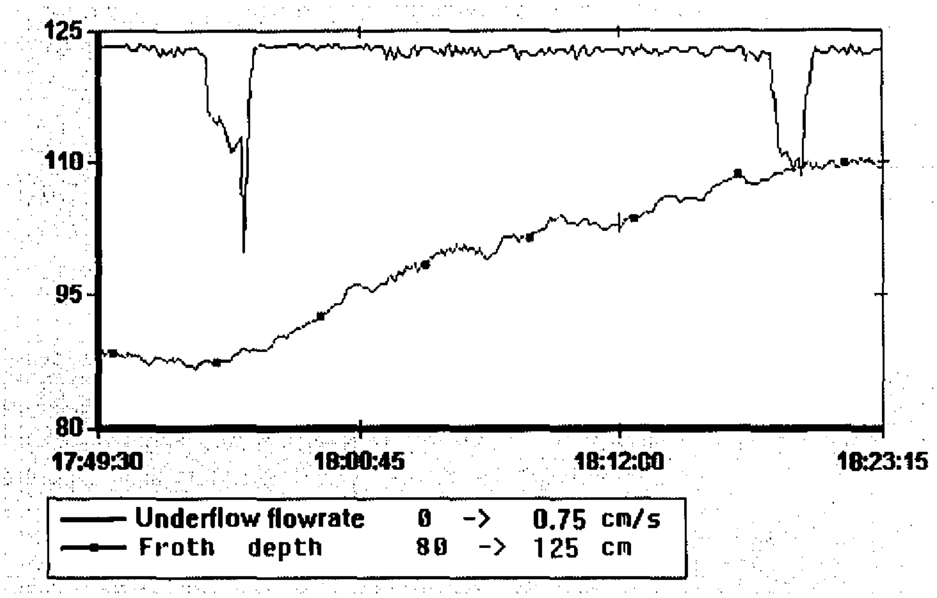


Figure 10. Underflow flowrate, bubbles effect in flowmeter

In some tests, the output signal dropped to zero. This condition remained until the trapped bubble was expelled.

4.1.1.3 Air flowmeter/controller

This is a dual function instrument that can measure the air flowrate, and control this flow by means of an external signal: a hardware **PID** controller performs the control function. The reading is given in volume of air at normal conditions per unit of time. The counter pressure downstream does not affect the reported flowrate, because what is sensed is the mass of gas passing through the meter. This was verified using a rotameter installed at the top of a 1 inch x 2 m column, taking readings for a fixed air controller setting, with the column empty and full of water: the rotameter gave the same values.

The air controller proved to be reliable, both delivering steady air flow, and robust enough to withstand abrupt changes in the settings from zero to the maximum flow range. Typically, the flowmeter reached a new setting in a matter of seconds with virtually no fluctuation. However, it is quite sensitive to the presence of liquid in the gas stream, which must be avoided.

4.1.2 Column controllability

In order to evaluate the process response to changes in parameters settings, an open loop test was run to establish the controllability of the column under normal conditions, and to evaluate the efect of typical disturbances.

The normal conditions of operation were established from the literature[7] and are presented in Table 3.

Table 3. Normal tests conditions

Flowrate	**Range** *cm/s*	**Normal** *cm/s*
Air:	0 to 3	1.0
Feed:	0 to 2	0.5
Underflow:	0 to 3	0.6
Washwater:	0 to 1	0.2

In the initial tests, some limiting conditions were identified: in order to obtain a stable froth and to ensure a continuos flow of overflow, it was necessary to maintain a gas holdup (ϵ_g) of, at least 10 % . Another restriction was the "churn- turbulent" condition (the whole column appearing to behave as froth) in which the interface was no longer visible: this condition usually happened when the gas holdup was higher than 25 %.

Gas holdup is dependent on the pore size of the sparger, the frother concentration, the air flowrate and to a minor degree the underflow flowrate.

In all cases the frother concentration was about 30 ppm of Dowfroth 250, at which point a minor fluctuation in frother concentration should not affect the process significantly.

Another limitation was that at low gas holdup a relatively high washwater flowrate was required to maintain a continuous froth overflow. At high gas holdup, however, the washwater flowrate required to maintain the overflow is reduced and eventually becomes unnecessary. This situation corresponds to a negative bias.

Similarly, all other parameters show a certain degree of interdependence, which should be taken in account when the test parameters of a given experiment are defined.

4.1.3 Controllability test

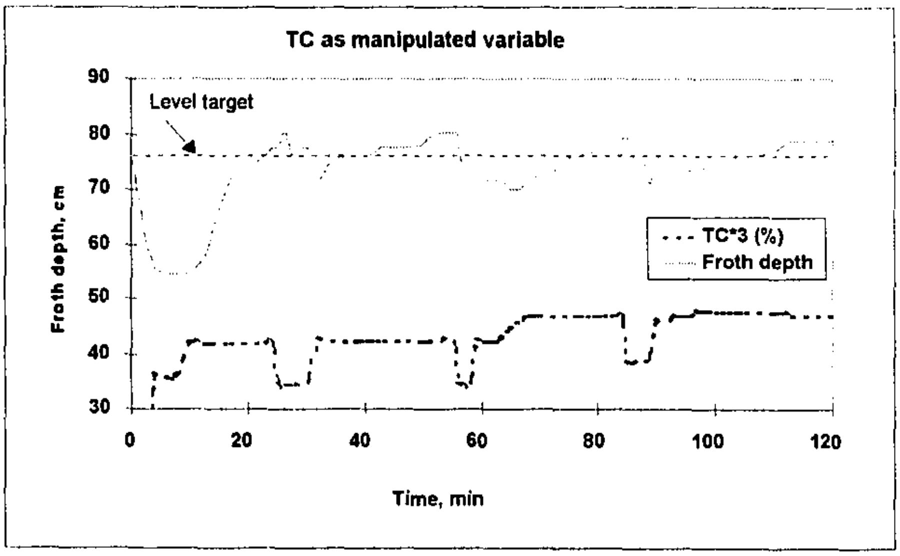


Figure 11. Controllability test

The controllability test, shown in Figure 11, was run under moderate conditions: gas holdup, 15 to 20 %; air flowrate, 1 cm/s; feed flowrate, 0.40 cm/s; washwater 0.20 cm/s; and, underflow, ~ 0.55 cm/s. All streams were taken from and returned to a single tank.

The objective was to try to keep the froth depth at a predetermined position (76.2 cm) under manual operation, and at the same time evaluate the effect of disturbances. The manipulated variable was the set point to the underflow stream pump (TC, given in % of the full range 4 - 20 mA). Figure 11 shows that the process is easily controlled, and that the pump response is fast enough to compensate for disturbances of the process. It should be mentioned that one major source of disturbance, in previous column testwork in the laboratory was air flowrate fluctuation, which is now overcome by use of the mass flowrate meter/controller.

In the following section, the pressure method used to calculate the froth depth, is presented and analyzed.

4.2 Level calculation, pressure method

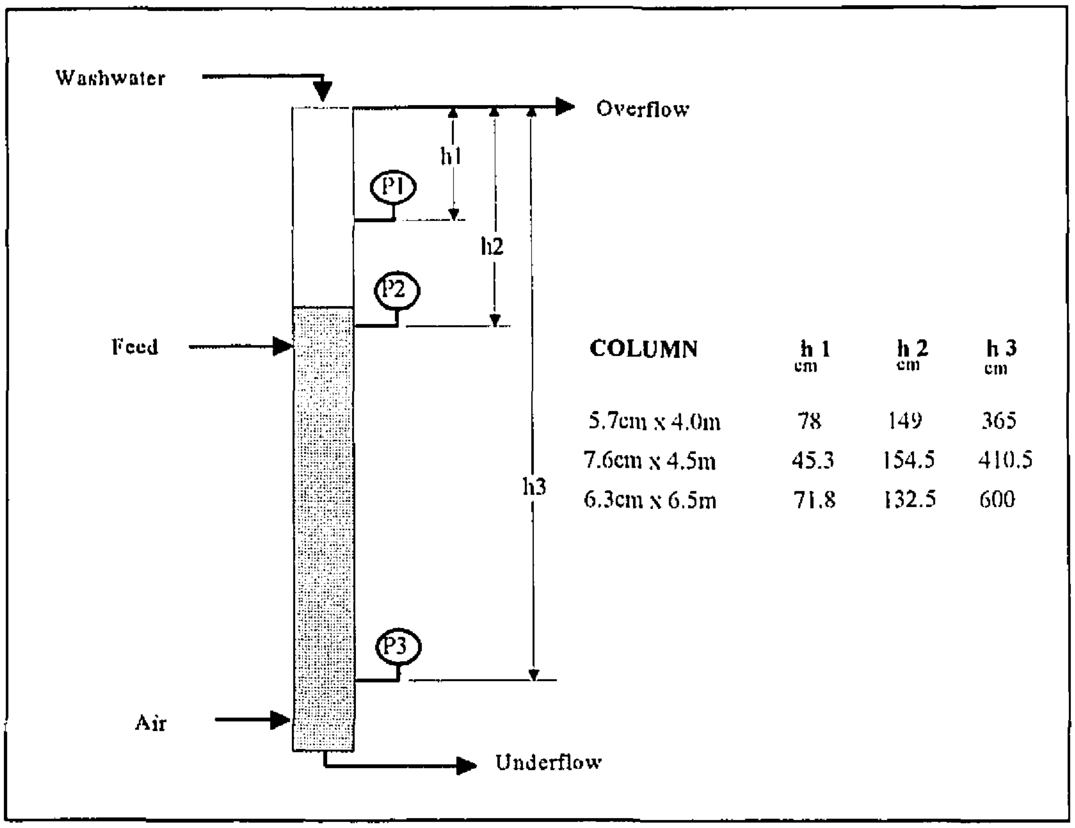
The pressure transducers were installed according to data given in Figure 12. The triple pressure transducer method was used to calculate the froth depth. In order to evaluate and compare results, blocks and chains to calculate the froth depth using one and two pressure transducers were also created in the database. The triple gauge method is the most accurate; however, its valid range of application is limited to the distance between the two top transducers (h1--h2). The other options (single and double gauge methods) have a wider valid range, and can be used to observe some behaviour beyond the h1--h2 range.

As shown in this figure the common practice is to use two transducers in the slurry zone and one in the froth zone. The general guidelines for positioning the transducers are:

a) Place the bottom pressure transducer (P3) close to the bottom of the column, but away from the gas injectors to reduce disturbances.

b) Place the top one (P1), around the highest expected level position.

c) Place the middle one (P2), close to the expected lowest position of the level.



COLUMN	h 1 cm	h 2 cm	h 3 cm
5.7cm x 4.0m	78	149	365
7.6cm x 4.5m	45.3	154.5	410.5
6.3cm x 6.5m	71.8	132.5	600

Figure 12. Position of pressure transducers

4.2.1 Equations used to calculate the level

The equations used to calculate level are readily derived from static pressure considerations. The equations to calculate the froth depth, for 1, 2 and 3 pressure transducer relevant to the set-up in Figure 12, are given below:

$$LEV1 = \frac{h_3 \rho_c - P_3}{\rho_c - \rho_f} \qquad (1)$$

$$\mathrm{LEV2} = \frac{h_2\left(\frac{P_3 - P_2}{h_3 - h_2}\right) - P_2}{\frac{P_3 - P_2}{h_3 - h_2} - \rho_f} \qquad (2)$$

$$\mathrm{LEV3} = \frac{h_2\left(\frac{P_3 - P_2}{h_3 - h_2}\right) - P_2}{\frac{P_3 - P_2}{h_3 - h_2} - \frac{P_1}{h_1}} \qquad (3)$$

All symbols are defined in the glossary of terms (Page I-8).

Equation LEV2 requires an estimate of the collection zone density, while LEV1 requires estimates for both zones. This problem is apparently obviated in LEV3: The two transducers in the collection zone allow for ρ_c while, the top transducer (P1) compensates for ρ_f. The explicit assumption is that the level is between P1 and P2. There are other implicit assumptions, however: The collection zone density is constant from P3 up to the interface; and the froth zone density is equal to the density above P1. In fact neither assumption is correct, the froth zone density in particular increases significantly on approaching the interface, as described in section 6.1.2. Nevertheless, it is anticipated that LEV3 will give the most accurate level estimation.

4.3 Automatic level control

The strategy to control the level, in stabilizing or regulatory control as currently practiced, is based on feedback control loops in which PID controllers are used to close the loop between the controlled variable (level) and the manipulated variable (underflow, washwater or feed stream).

The feedback loop may be implemented using hardware (physical controllers), or may be created in software. Because of some advantages like: lower cost, installation on-line not required, and simplicity to change settings; the current preference is the second option.

4.3.1 Level feedback control loop

The block diagram representing the feedback loop used to control the level, is presented in Figure 13.

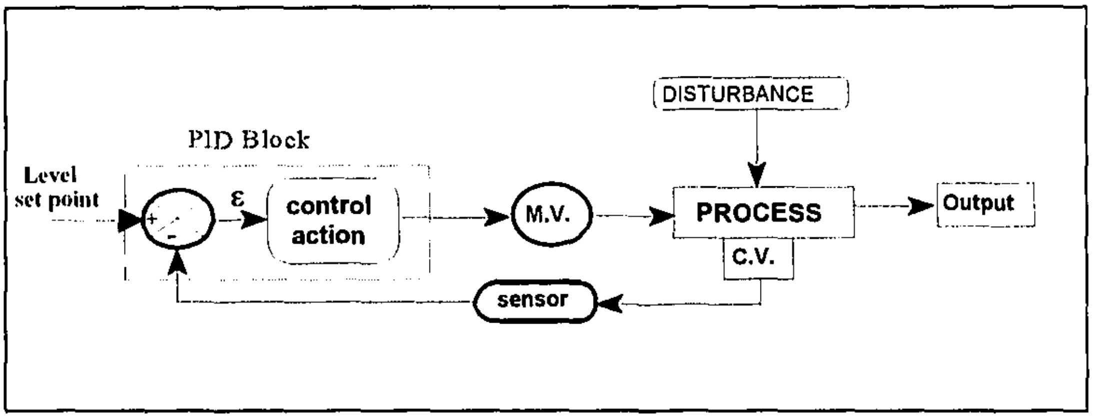


Figure 13. Feedback control loop

This diagram is a schematic representation of a single control loop. In our system there are three loops in parallel, which maybe used to keep the level at a given point set by the operator in **view,** alternatively by manipulation of: the underflow, the washwater or the feed stream, This value (level) is set simultaneously in the three PID blocks (***PID_F, PID_W*** and ***PID_T***) by the fanout block: ***FAN_SET***, as depicted in Figure 5 (page 21), using the analog input block ***SAI_SET***, created in the simulated driver.

The controlled variable (C.V.), in reality represents the pressures taken at points h1, h2 and h3, by the sensors P1, P2 and P3. These values are fed to the calculation block ***LEV3*** which calculates the level and the output is sent in parallel to all PID blocks by the fanout ***FAN_LEV*** block. This last operation, due to limitations in the software was not easily performed, and it was necessary to include the analog input blocks *SAI_W* and *SAI_T*, using the simulated driver, to create chains to accomplish the fanout task.

The program is set to start in manual option, i.e. program block :***MODE_M***, is active, and all the other *MODE_?* blocks are inactive. On the screen (Figure.5) behind the grey pushbutton named **MANUAL,** a red rectangle appears. In this condition, selector switch blocks: ***FSS, WSS,*** and ***TSS,*** will use **input 2,** whose values are set by the operator in **view** and go, respectively, to the output blocks ***FC, WC*** and ***TC***, which control the pumps.

In order to operate in automatic mode using the underflow as manipulated variable, with the mouse, we may activate the **AUTO_T**, pushbutton in ***view*** (on the control screen) and then it will deactivate all program blocks *MODE_?*, including *MODE_M*, and will activate the program block ***MODE_T*** (in this case, the selector switch block ***TSS*** will use its **input 1,** which is set by the ***PID_T*** PID block, the other two pumps will be set by the operator through ***view***). The red rectangle behind the MANUAL pushbutton will disappear, a red bar above the AUTO_'s pushbuttons will appear, and the small white rectangle above AUTO_T will blink.

The *MODE_?* program blocks can link the pumps to the corresponding PID blocks or to the value entered by the operator in the yellow rectangles placed just below each pump in the control screen in *view*, by changing the input to the switch selector blocks ***FSS, WSS*** or ***TSS*** placed just before the output blocks, ***FC, WC*** and ***TC*** (Figure 5, page 21).

4.3.2 PID algorithm used in FIX-DMACS

$$\boxed{\Delta y_n = K_p \ \beta (E_n - E_{n-1}) + \frac{T(F_n - Y_{n-1})}{T_i} + \frac{T K p E_n}{T_i} + \frac{K_p \ T_d \ \gamma}{6 \ T (T_d \ \alpha + 1)} * (E_n + 3E_{n-1} - 3E_{n-2} - E_{n-3})} \quad (4)$$

Equation (4) was used to calculate the output action of the PID blocks in FIX-

DMACS. This is known as the ***velocity form*** of a digital PID algorithm[8,9], where:

Δy_n,	Increment of the PID output at current time.
Kp(Kc),	Proportional controller constant .
E_n,	Error at present sampling time.
E_{n-1},	Errors at given previous sampling time
T,	Sampling time (scanning time at which errors are calculated).
Y_{n-1},	Output of controller in previous to current sampling time.
$T_i (\tau_i)$,	Integral time constant or Reset time (minutes/repeat).
$T_d(\tau_d)$,	Derivative time constant, or Rate constant (minutes).
F_n,	Feedback tag value.
α,	Derivative mode filter.
β,	Proportional action constant.
γ,	Derivative action constant.

Note.- The terms in parenthesis are used in section 4.4.
See glossary of terms (page I-8).

All these terms are more or less standard in discrete PID algorithms, except F_n, which is an option of FIX-DMACS, to prevent "***wind-up***" or saturation of the controller output produced, for example, by failure in the instruments or circuitry. The wind-up problem is related to the integral action, third term in equation (4), which increases the PID output at each sampling time as long as an error is reported. This action, is helpful in reducing the error to zero; however, sometimes due to imperfections in the systems, small reported errors may increase (or reduce) the controller output, driving the manipulated variable either to saturation, or closing (or stopping) it. None of these situations is desirable.

In the PID blocks, the proportional band (PB) replaces the proportional constant (Kp), according to the relation: Kp = 100/PB .

Depending on the values assigned to a given parameter, the PID blocks can be used as only proportional (**P**), proportional-integral (**PI**) or proportional-integral-derivative (**PID**) controllers.

4.4 PID parameters calculation

The parameters of a controller determine how the controller reacts to a given stimulus represented by a change in the controlled variable

To calculate the parameters of the controller (P, PI or PID), for a given process, two main methods are used: analytical calculations or empirical approximations. The first is based on mathematical models that try to simulate the transfer function of each element in the control loop. It is then possible to calculate the range of parameter values in order to get a stable system. The process transfer function can be solved and plotted using different parameter values to verify the stability of the system and simulate the control action of the feedback loop. A good example of this method, applied to level control in a flotation column is given in the literature[13]. A limitation of this work, is that the overflow flowrate is assumed to be constant, while in reality it changes considerably according to the level position. However, this appears to be unimportant because the simulated response of the controller fitted well with the response obtained in laboratory column test, even in the case where solid slurries were employed. The level range tested, however, was relatively narrow.

The advantage of the analytical method is that it is off-line, and does not involve involve actual tests, which are expensive, especially at plant scale. The results obtained seem to simulate the process accurately enough. Nonetheless, a fine tuning of the parameter values is always necessary in the industrial application.

The empirical methods, are favoured when equipment is available for testwork, as in our case. The two best known methods are the Ziegler-Nichols and the Cohen-Coon methods[4,9]. The second one does not require the inclusion of a control loop because it is conducted in open loop, while for the first one, the test is performed in closed loop. Both methods yield practically the same results[4].

The Cohen and Coon method was applied in this project because of its greater simplicity.

4.4.1 COHEN and COON method

This is a procedure which requires the use of at least laboratory scale equipment.

It was found that once a set of parameters for a **PID** are established, they apply to a wide spectrum of column operation; therefore, it is anticipated that parameters found at the laboratory scale may apply well to industrial columns. The only uncertainty in our case would be the effect of a solid phase (slurry), which may affect the density profile of both the froth and collection zones. In this case further fine tuning of the controller could be needed, starting with the values found in the laboratory.

The Cohen and Coon method, well described in reference 9, consists in finding the open loop response of the process to a step change in the selected manipulated variable, and then using the data graphically to calculate the parameters according to empirical equations.

The conditions to fix the magnitude in the step of the manipulated variable are summarized as follows:

- The response of the controlled variable, level in this case, must not exceed the valid range. Before imposing the step change, the level must be in steady-state, inside the valid range for equation LEV3 (h1--h2), and it should reach a new steady-state inside this range.
- The change in the controlled variable must be large enough to avoid confusion with the normal oscillations encountered in steady-state.
- The time required to reach the new steady-state must be short enough, in such a way that the variables assumed to be constant during the process will not be significantly affected by external effects, such as power supply voltage, air-line pressure or ambient temperature fluctuations.

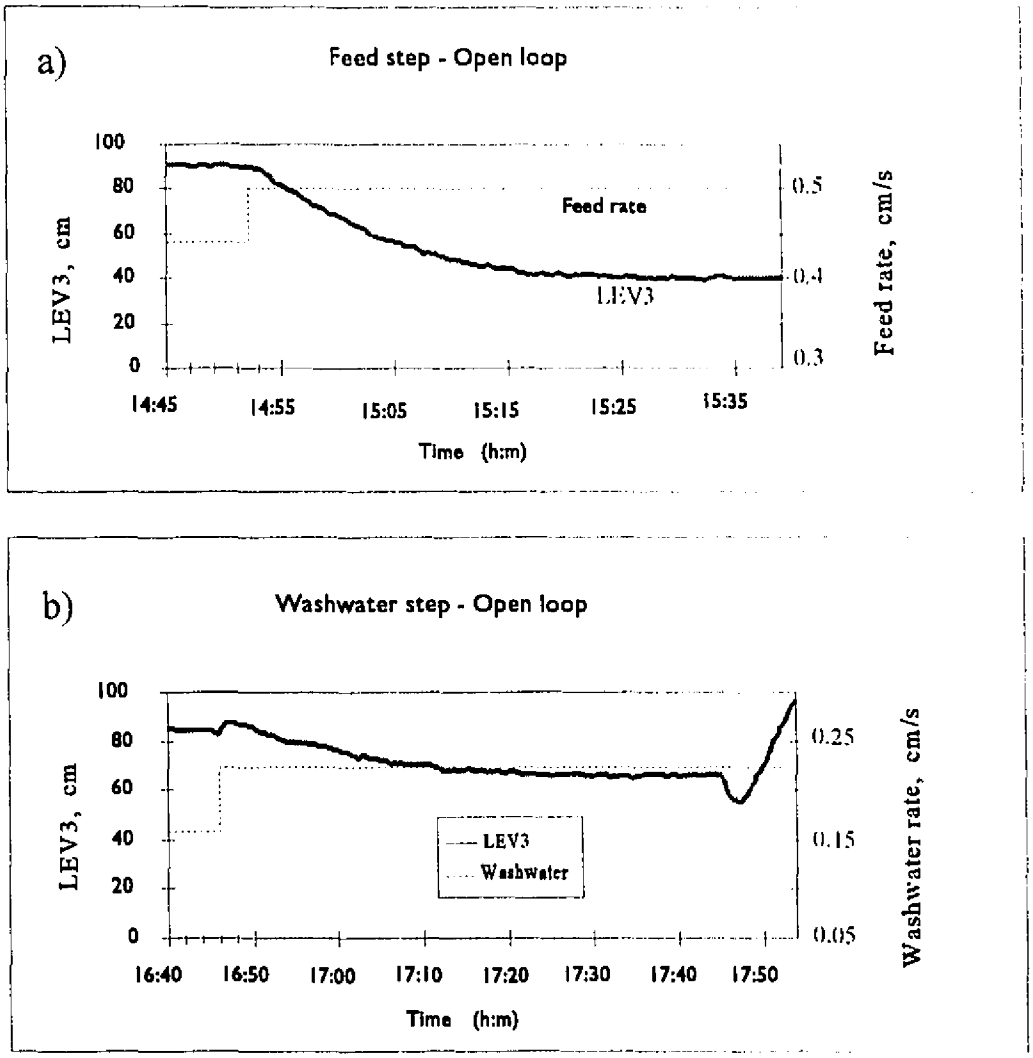


Figure 14. Open loop response to steps in Feed and Washwater

Figs. 14 and 15 depict the open loop response curves of the process to step changes in the underflow, feed, washwater and air flowrates.

Figure 15 a, includes the construction lines required in the calculation of the PID parameters using the Cohen and Coon method.

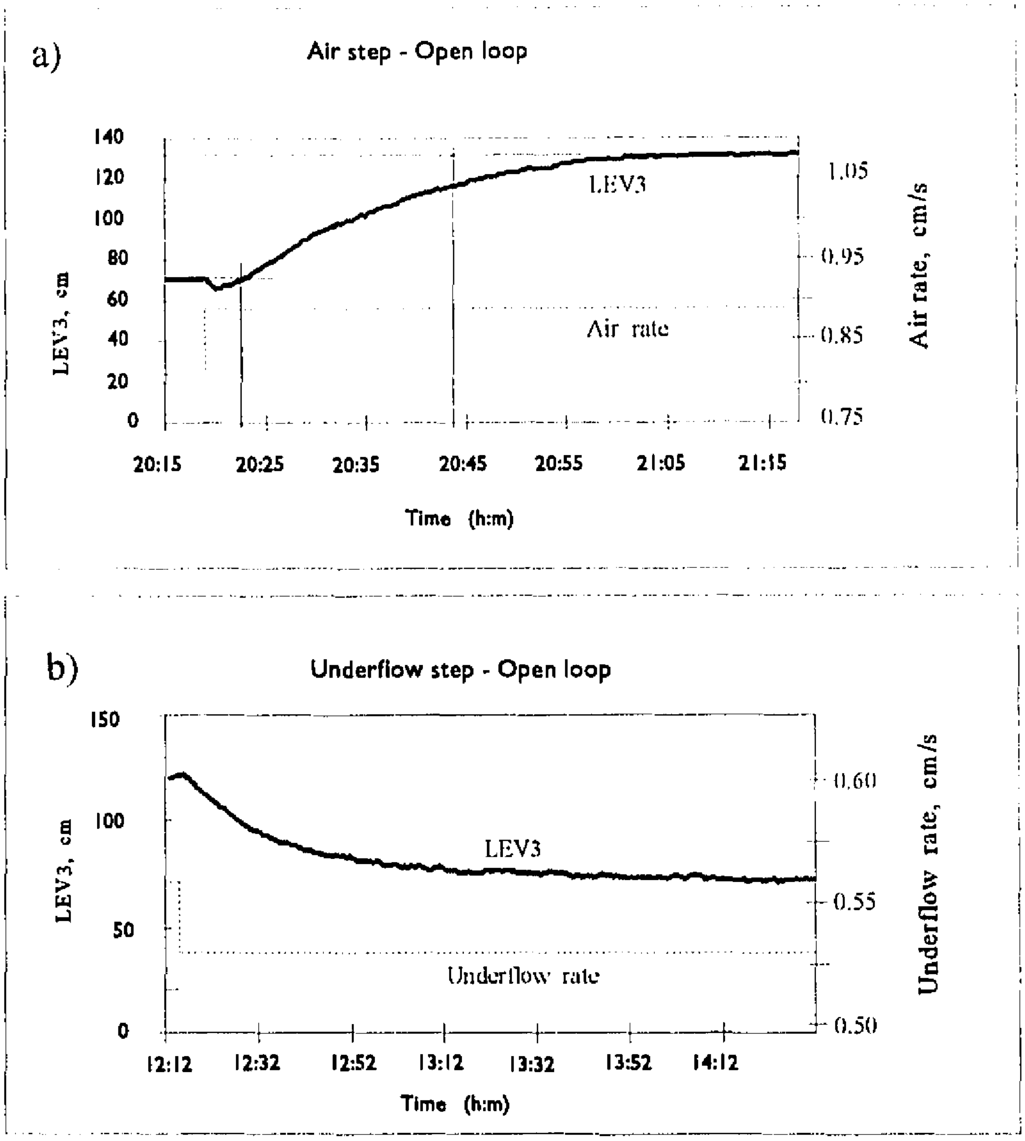


Figure 15. Open loop response to steps in Air and Tailings

By the shape of these curves, the response to step changes in both underflow and feed behaves as typical first order with time delay, and steps in washwater and in air produce an inverse response. In the case of air, during the transient state, initially the calculated level changes in one sense and then, after a few minutes changes to the other sense overcoming the initial change and behaving again as a first order response.

The parameter estimations are presented in tables 4, 5, 6 and 7.

Table 4.- General data, open loop response curves

K_p, Process gain = $\Delta B / \Delta A$, [cm/mA]
T_d, dead time, [min]
ΔA, step in M.V., [mA][1]
M.V., Manipulated Variable
K_c, Proportional control gain = 100/PB

τ, time constant = ΔB / S, [min]
S, slope (at sigmoidal point), [cm/min]
ΔB, change in C.V. (LEV3), [cm]
C.V., Controlled Variable
PB , Proportional band

M.V.	ΔB	ΔA	Td	S	Kp	τ
Underflow	-49.5	-0.6 mA	0.25	-2.20	82.5	22.5
Feed	-51.4	0.5 mA	0.20	-3.55	-102.8	14.5
W.W	-17.8	1.0 mA	4.40	-1.48	-17.8	12.0
Air	62.1	0.2 V	3.73	3.14	310.5	19.8

Valid range for controlled variable: 45.3 to 154.5 cm.

Feed, underflow and washwater full range: 4 to 20 mA.

Air full range of manipulation: 0 to 5 volts.

4.4.1.1 Proportional controller

The parameter for proportional control is calculated using the following empirical equation:

$$K_c = (\tau / K_p T_d) (1 + T_d / 3\tau) \qquad (5)$$

Solving this, using the data in Table 4, gives:

---

[1] Units depend on manipulated variable, for underflow, feed and washwater is in mA, while for Air manipulation is in volts.

Table 5. Proportional control parameters

M.V.	Kc	PB
Underflow	1.09	91.33
Feed	-0.71	-141.14
W.W.	-0.17	-581.58
Air	0.02	5503.72

4.4.1.2 Proportional-Integral controller

The equations to calculate the PI controller parameters are:

$$\tau_i = T_d \left[\left(30 + 3T_d/\tau \right) / \left(9 + 20T_d/\tau \right) \right] \tag{6}$$

$$K_c = \left(\tau/K_p T_d \right) \left(0.9 + T_d/12\tau \right) \tag{7}$$

The calculated parameters for PI control are presented in Table 6.

Table 6.- Proportional-Integral controller parameters

M.V.	Kc	PB	τ_i
Underflow	0.983	101.75	0.81
Feed	-0.636	-157.35	0.65
W.W.	-0.143	-701.37	8.38
Air	0.016	6387.82	8.93

4.4.1.3 Proportional-Integral-Derivative controller

$$K_c = \left(\tau/K_p T_d \right) \left(4/3 + T_d/4\tau \right) \tag{8}$$

$$\tau_i = T_d \left[\left(32 + 6T_d/\tau \right) / \left(13 + 8T_d/\tau \right) \right] \tag{9}$$

$$\tau d = Td \left[4 / (11 + 2Td/\tau) \right] \qquad (10)$$

The calculated parameters for the PID controller, are presented in Table 7.

Table 7.- Proportional-Integral-Derivative controller parameters.

M.V.	Kc	PB	τ_I	τ_d
Underflow	1.46	68.61	0.61	0.09
Feed	-0.94	-106.07	0.49	0.07
W.W.	-0.22	-458.01	9.44	1.50
Air	0.02	4237.32	8.52	1.31

Using these values, a series of tests were run to tune the system, evaluate the quality of the control, evaluate the accuracy in level estimation, and to evaluate the behaviour of the system during both transient and steady-state conditions.

The analysis of the response to step changes in open loop, and the results obtained in the different evaluation tests, are presented in the next two chapters.

CHAPTER 5 - RESULTS AND DISCUSSION, PART I

OPEN LOOP AND LEVEL CONTROL TESTS

In the first part of this chapter, the results of tests run to tune the controller, the effect of simulated disturbances and the quality of the level control are presented. In the second part, tests run to evaluate the accuracy of the level calculation, are presented, together with discussion.

In the execution of this thesis some problems related to the accuracy and response of the equation used to calculate the froth depth (LEV3) became apparent. These problems are mainly related to the valid range of equation LEV3, and its response when the level is placed outside this range; tests to attempt to correct the errors, and the use of LEV2 or LEV1 as alternatives are discussed in the second part of this chapter.

5.1 Open loop response

The analysis of the response of the system to step changes of the manipulated variable in open loop (Figures 14 and 15) demonstrate that the manipulation of feed and underflow, produce a first order response with a relatively short time delay. This means that both can easily be used as the manipulated variable in a feedback control loop.

The air manipulation produces an inverse response, which makes it a poor choice for control. In this case, more sophisticated strategies instead of simple feedback loops are recommended, i.e. the Inverse Response Compensator algorithm[14], which uses a process model to predict the response, and compensates the inverse behaviour through a parallel circuit.

The washwater step change, also apparently produces an inverse response. This is not a true inverse response of the process but only in the calculated level; this will be further analyzed in the next section.

5.1.1 LEV1, LEV2 and LEV3 response to a step change in washwater

It is important to note that the step change in washwater produces an inverse response in the calculated froth depth, and is not necessarily the same for the actual froth depth. For example, at the beginning of the transient response produced by the change in washwater flowrate the level remains unchanged while the froth absorbs or releases a certain volume of liquid producing a relatively long time delay. After this delay, when the froth reaches a new liquid holdup equilibrium, it starts to take/release liquid from/to the slurry changing the level. Normally, the froth depth is reduced for an increase in washwater flowrate, and vice versa. In the case of weak froth, the opposite may occur (froth depth increase for an increase in washwater rate); but, in the case of thick froth, the change in washwater may not affect the level (i.e. high negative bias).

The time response of the system to a step change in the washwater flowrate using LEV3, LEV2 and LEV1 to calculate the level, is presented in Figure 16.

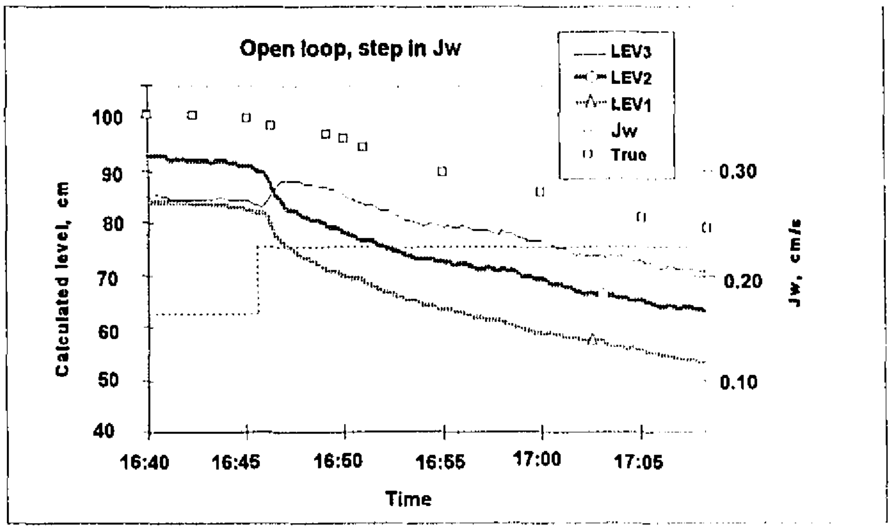


Figure 16.- LEV3, LEV2, LEV1 response to step in Jw

<u>Note</u>: Points reported as true level are estimated from equation LEV2 based on average values of froth density at each point, and are used only to evaluate the trend in change in the true level.

In this figure, the initial response of LEV3 to an increase in washwater, shows an increment in the froth depth (interface goes down), while in reality the interface starts to go up. As for LEV1 and LEV2, both are able to follow or "anticipate" the real change.

a) LEV3: The analysis of this response is referred to equation 3; the positive step in washwater, initially affects the calculated froth depth, according to the approximate model:

$$L_{(2)} = [L_{(1)} - 2.5\Delta p]/[1 - \Delta p/18] \qquad (11)$$

Restrictions: 7.6 cm x 4.5 m column, open loop, initial stage transient produced by a step change in washwater, gas holdup ~20 %.

$L_{(1)}$, LEV3 value before the step, cm.

$L_{(2)}$, LEV3 value after the step, but before true level is affected, cm.

Δp, Increment in pressure, produced by the step change, cm of H_2O.

Assuming $L_{(1)} = 100$ cm , and solving equation 11, for different increments in Δp:

Δp, cm of H_2O	**$L_{(2)}$, cm**
0.5	101.6
1.0	103.2
5.0	121.2
10.0	168.8

This shows that in the initial stage of the transient response LEV3 increases in value in proportion to the magnitude of the step change in washwater. If these values were fed to a control loop, it would cause an immediate response that may not only induce oscillation but could also lead to an "out-of-control" condition.

b) LEV2: The analysis of this response is simpler than for LEV3. In equation 2, the only variable affected by the step is P2 which is increased proportionally. Any increase in P2 reduces the value of LEV2, so that in the initial stage of the transient response, the calculated froth depth "anticipates" the effect that the step is going to have on the true froth depth. However it is important to remind that the steady-state error of LEV2 will depend on the change in froth density at the new equilibrium value of liquid holdup. The error is increased or reduced according to the initial value of ρ_f assumed in equation 2.

c) LEV1: The same analysis performed for LEV2 applies here, except that the affected variable is P3 instead of P2. The general assumption is that the collection zone density remains constant.

It can be seen that neither LEV2 nor LEV1 generated an inverse response and can advantageously replace LEV3 in some feedback control loop applications.

5.2 Level control tests

Several tests were run to find the effect and differences among **proportional**, **proportional-integral**, and **proportional-integral-derivative** control, as well as the effect of different values of the control parameters. In all these experiments, LEV3 was used to calculate the froth depth, while the true depth was determined by visual observation.

In these tests, the system was set manually with the level inside the valid range (h1--h2). When the level was stable, or changed at a speed of less than 2 cm/min, the switch to automatic mode was made. If the controller was able to keep the level inside the valid range, a 10 cm change in the level set point was imposed to simulate a disturbance then, if the controller was able to drive the system to a new steady-state (level constant, inside the valid range) and hold it for at least 20 minutes, we concluded that the level was under control.

Initial experiments were run applying the parameters calculated in the previous chapter, for proportional (**P**), proportional-integral (**PI**) and proportional-integral-derivative

(**PID**) control.

To tune the controller parameters, steps of 20% above and below the values obtained with the Cohen and Coon method were initially tested to find the limits of application of a given system. Subsequently steps of 10% inside these limits were made to find the optimal (tuned) point.

The criteria to establish the limits of application were: the ability to bring the system to steady-state, in a reasonable time (~ 10 min) after the disturbance was introduced; and, low amplitude of level oscillation in steady-state. The control was deemed unacceptable, when the controller output signal (sent to the manipulated pump) was oscillating with an amplitude greater than 0.5 mA.

5.2.1 Proportional control

From Table 5 (Page 45), it is concluded that the best manipulated variable is the underflow, because its proportional band (PB) is relatively low (91.3), meaning that it is possible to apply high correction action (output gain) without introducing oscillations or de-stabilizing the system. The use of feed also gave a reasonable, absolute value of PB (-141.1); however, for washwater and air PB values were too high indicating that low proportional gain should be used by the controller. Consequently, in order to keep the system stable, the change in manipulated variable must be very small; consequently, the controller may not be able to compensate for even relatively small and slow disturbances. In fact, it was found that in the two phase (air/water) system, with no deliberate disturbances, the system was unable to control the level using washwater as manipulated variable, probably because of the higher time delay and the inverse response produced when this variable is manipulated (Figure 14, page 43). The use of air as manipulated variable is expected to give an even worse result.

In proportional control, only the use of tailings as the manipulated variable was tested. The results show that the control obtained was not robust, which discouraged the use of any other parameters as manipulated variables.

The initial test value for parameter PB was 100%. Figure 17 presents the data collected in this experiment, revealing a problem produced by the software when the system was toggled from manual to automatic operation at 12:19. The underflow pump signal dropped from 10.5 mA to close to 4 mA, stopping the underflow pump. Even when soon restarted, it was unable to compensate for the rapid increase in level (reduction in froth depth) which went above h1 (tap of P1), the upper limit of the valid range of LEV3. After ~ 12:22 the value of LEV3 remained constant (giving a value ~ h1, 45.0 cm) and the controller output also remained constant, implying steady-state condition. This is false, however, because equation LEV2 showed the level was still changing.

The system was not able to keep the level inside the valid range because the response of the controller, after the step change, was not high enough (PB value was too high, i.e. low controller gain). In subsequent tests, lower values of PB were used and it was found that, in the range from 80% to 30 %, the system was able to regain control and keep the true level inside the valid range.

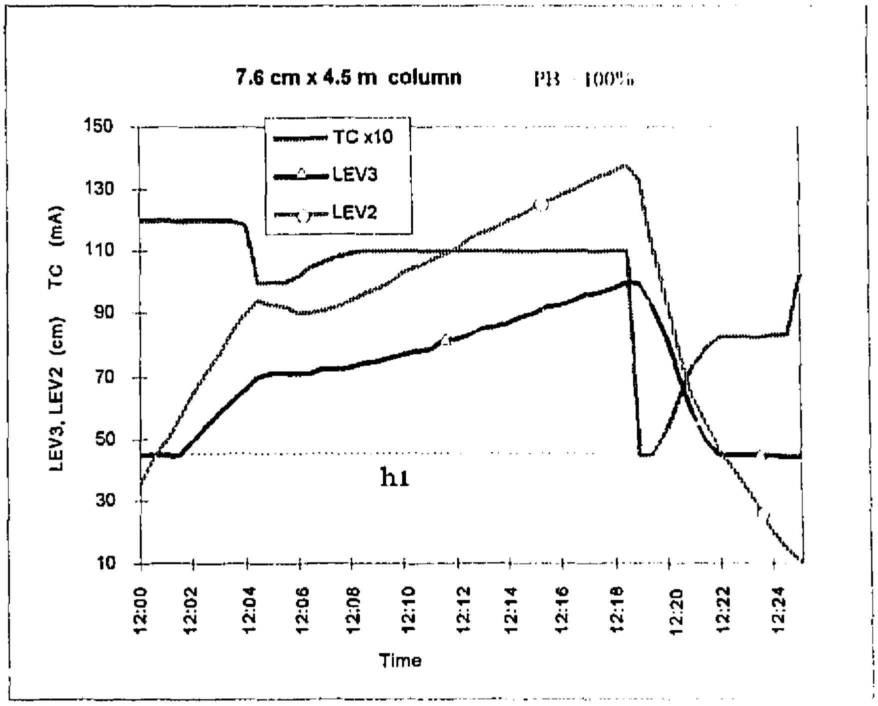


Figure 17.- Proportional control, PB = 100 %

The process response to manipulations of the underflow flowrate, in proportional level control, with a tuned value of 60% for PB, is presented in Figure 18.

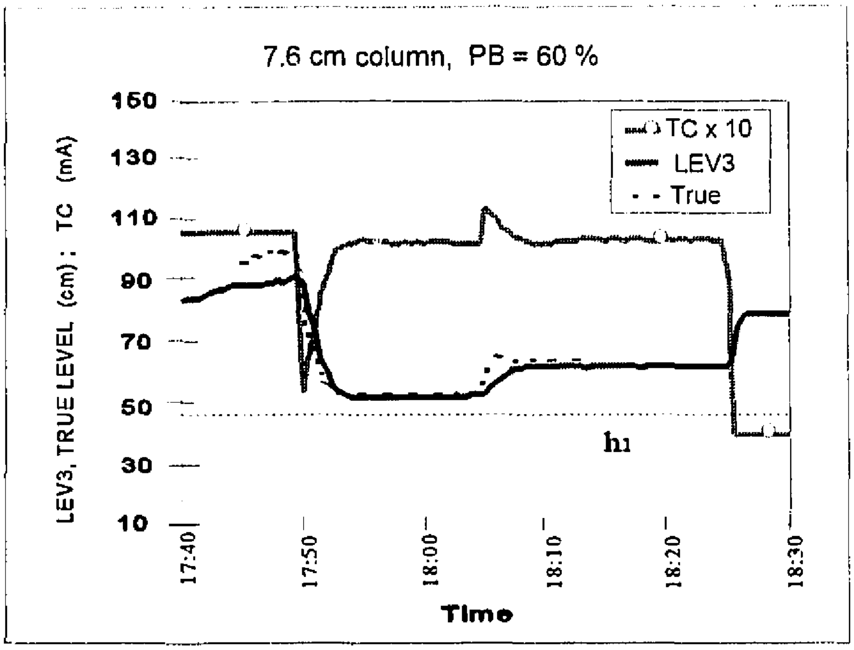


Figure 18.- Proportional control, PB = 60 %

Test conditions:

Column size:	7.6 cm x 4.5 m		
Flowrates (cm/s):	Jg = 0.9	Jw = 0.25	Jf = 0.50
Initial settings:	Level set point (LSP) = 100 cm	Mode: MANUAL	
Procedure:	17:50, mode switched to AUTO_T.		
	18:05, LSP changed to 110 cm.		

In order to follow the control action, the output of the controller, TC x 10, is included in the plot. The important features in this figure are: stable level control is possible and appears to be quite good, because the new steady-state is reached relatively fast (< 3 min.), and the underflow manipulation is soft under steady state.

The main problem occurred when the system was switched to automatic. At this moment, even if the calculated level (LEV3 ~ 90 cm) was relatively close to the set point (LSP=100cm), and the underflow pump was set to 10.5 mA, value close to its equilibrium point, ~ 10 mA, the software produced a jump in the underflow set point (output of the proportional control) dropping it close to 5 mA, and causing the pump to stop. Once the system is in automatic mode, the level manipulation was done very easily, as shown by the 10 cm level step change at 18:05 . The system executes the step and reaches a new steady-state in ~ 3 min, without producing overshot in the calculated froth depth , and only a minor one in the true level.

The initial jump disabled the application of this kind of control because the level could go outside the valid range of operation (which happened many times). As seen in Figure 18, the true level is close to the top pressure transducer position, h1 = 45 cm, the lowest limit of froth depth in the valid range for equation LEV3.

Another disadvantage in this type of control, is that steady-state is produced as soon as no more change in controller error (LEV3 - level set point) is produced, no matter what the value of this controller error may be. In Figure 18, the first steady-state is produced with LEV3 ~ 55 cm, while the set point was 100 cm.

In relation to the jump produced in the controller output when the system is switched from manual to automatic, FIX-DMACS gives the user two options to reduce or avoid this effect, these are:

a) Track b) Balance c) None

The Balance option produces the smoothest switch to automatic operation. In the track option, the output to the manipulated variable jumps to the minimum value allowed for this variable (4.0 mA) producing a large disturbance leading to an out-of-control condition (level above h1). On the other hand, both: the Balance and None options, produce a jump to an intermediate value (between the current output and the minimum value). This allows the controller to regain control before the level moves "out-of-valid-range". The magnitude of the initial change depends upon the initial trend of the level, the initial controller error (LEV3-Level set point), and on the value of the PB parameter.

5.2.2 Proportional-Integral control

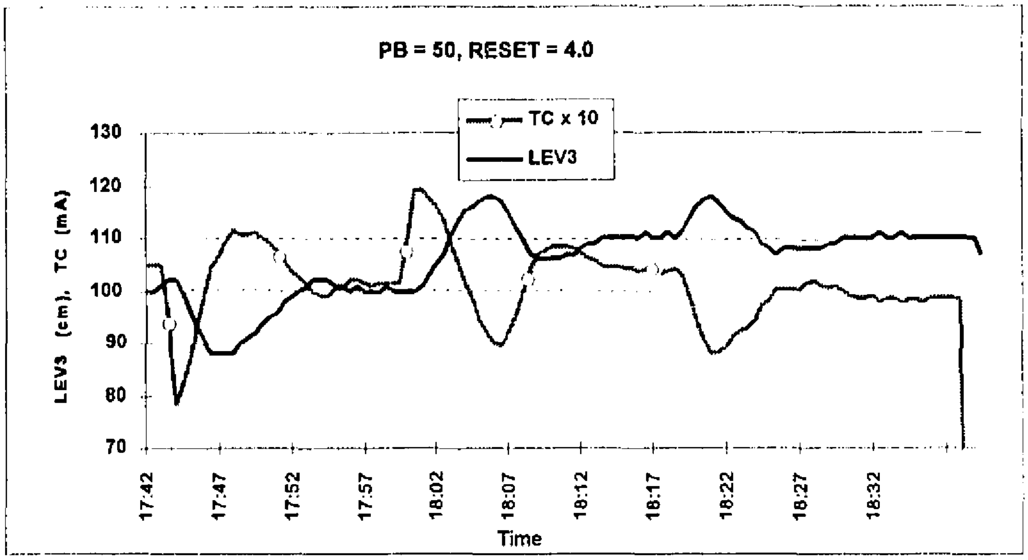


Figure 19.- Proportional-Integral control, TC as M.V., J_g disturbance

Test conditions

Column size:	7.6 cm x 4.5 m	
Flowrates (cm/s):	J_g = 1.3 J_w = 0.23 J_f = 0.65	
Initial settings:	LSP = 100 cm	Mode: MANUAL
Procedure:	**Time**	**Action**
	17:43	Mode to AUTO_T
	17:59	LSP to 110 cm.
	18:19	J_g to 1.4 cm/s

The integral term of the PI controller, produces two main advantages over the proportional controller: 1) In steady-state the level offset or controller error (LEV3 - LSP) is reduced to zero; 2) The initial controller output change, produced when the system is switched from manual to automatic, is compensated by the integral action, thus avoiding the "out-of-valid-range" condition. Unfortunately, tuning is more complicated due to oscillations introduced by the integral action.

Figure 19 shows the results using the best set of parameters, PB = 50 and Reset (or integral-time constant, τi) = 4.0 (minutes/repeat). These values differ from those obtained with the Cohen-Coon method: PB ~ 100 and τi ~ 0.8 (Reset) which, even if the system is still stable (convergent toward the LSP), the oscillation induced by the integral action is large in amplitude and may lead to an out-of-valid-range condition. Another problem produced using such a strong integral action (lower the value higher the integral action) is that the time required to reach a new steady-state is quite long (~ 30 minutes).

The time required to reach steady state, in both manipulations (step in LSP and change in Jg) is ~ 10 min, and the overshoot in calculated level related to the set point, is high ~ 10 cm (AUTO_T mode). This overshoot may not present too big a problem, but in the initial switch from manual operation, the overshoot was even higher and could take the true level outside the valid range. For this reason, in order to use a PI control in industrial columns, different parameters for the controller should be employed for start-up and for normal operation. Air flowrate as a source of disturbance, seemed not to represent a difficult problem, unless the level were placed too close to the limits of the valid range.

5.2.3 Proportional-Integral-Derivative control

This type of control is more sturdy and reliable than the PI and P controllers, being able to control the level over a wider range of variable settings than the other two. Another advantage is that this controller does not need a fine tune-up of the parameters, and a given set of parameter values can be applied to exert level control by manipulating underflow, feed or washwater, without the need to change them. It was possible to perform level control in columns of different diameters and heights and different pump size without re-tuning the PID parameters.

To tune the PID parameters the initial set was:

$$PB = 70 \qquad \tau i = 0.5 \qquad \tau d = 0.1$$

corresponding to the values calculated with the Cohen-Coon method. It was found, however, that it was possible to obtain stable conditions over a wide range of values:

PB from 100 to 300 %, τ_i from 0.05 to 2.0 and τ_d from 0.01 to 0.5

The best set of values, using underflow flowrate as manipulated variable, was:

$$PB = 180, \quad \tau_i = 1.2 \quad \text{and} \quad \tau_d = 0.05$$

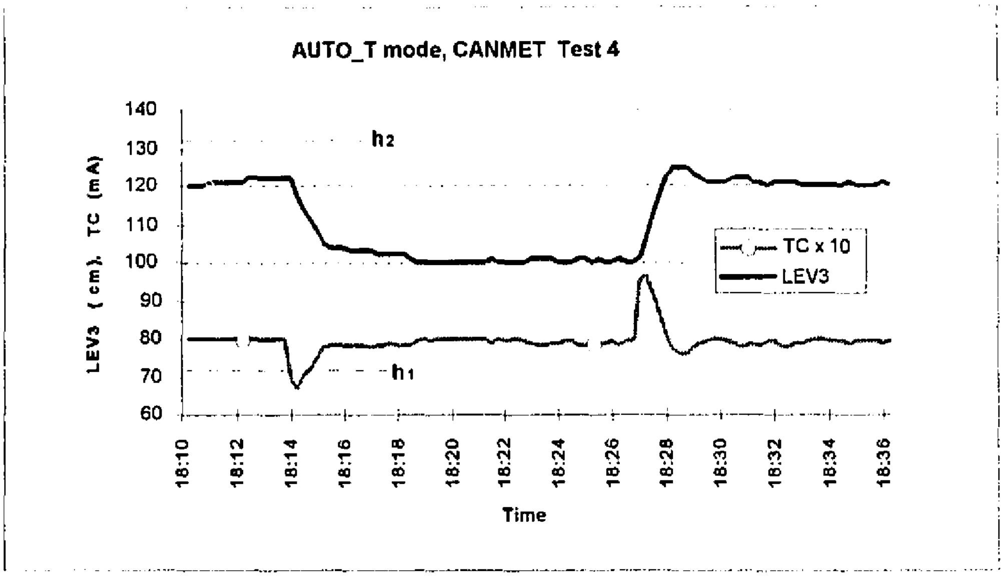


Figure 20.- PID control, underflow as manipulated variable

Test conditions

Column Size:	6.3 cm x 6.5 m	
Flowrates (cm/s):	$J_g = 1.6$ $J_w = 0.23$ $J_f = 0.84$	
Gas holdup:	21.6 %	
Initial settings	LSP = 100 cm	Mode: MANUAL
Procedure:	**Time**	**Action**
	18:14	Mode to AUTO_T
	18:26	LSP to 120 cm

Figure 20 presents the result obtained using the last set of values as PID parameters. In this case, the difference between the level set point and the calculated level is reduced to zero after ~ 4 minutes, with a relatively small overshoot during the transient state. The manipulation of the TC signal by the controller is quite soft, thus it is concluded that the quality is better than that achieved with the PI controller. Using this type of control, tests where conducted to evaluate the effect of disturbances imposed by changes in flowrate of streams other than the manipulated one.

5.3 Disturbances effects, PID control, underflow as manipulated variable.

Figure 21 shows the effect a step changes in the air flowrate, from 1.5 to 1.8 L/min (J_g from 1.0 to 1.2 cm/s), to simulate an air disturbance.

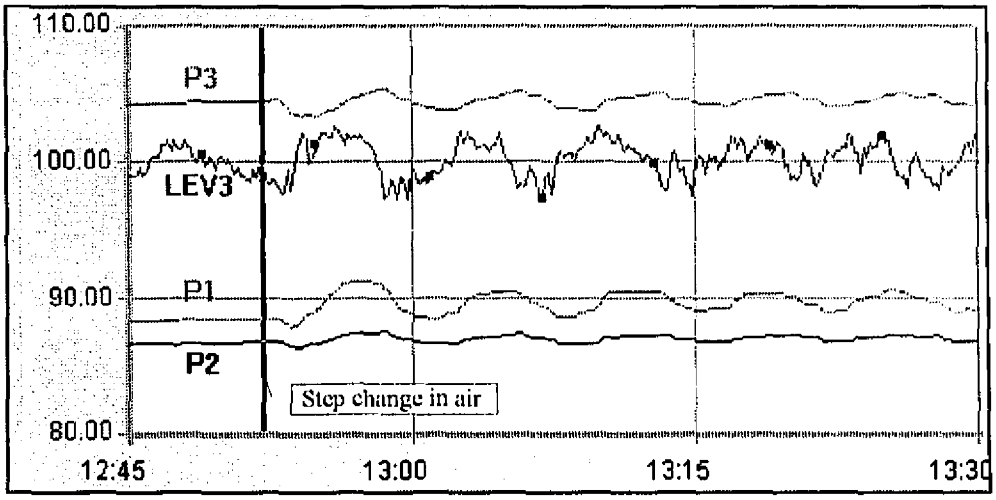


Figure 21.- PID control, TC as M.V., air disturbance

In this figure, the pressure transducer readings are plotted on different scales. An air step change (~ 20%) was introduced at 12:52 and the response of the controller was fast enough to keep the calculated level inside the range of ± 2 cm. However an oscillation is observed in the pressure readings, which remained for more than 30 min after the air step change.

In the test, corresponding to Figure 22, a change from Jw = 0.15 to 0.19 cm/s, was introduced at 14:43 to simulate a washwater disturbance. The effect of this step was insignificant. A new steady-state was reached in less than two minutes and virtually no level change was observed. This confirmed the that the response of the system to a change in underflow flowrate has a much faster effect on level than the response to a change in the washwater flowrate.

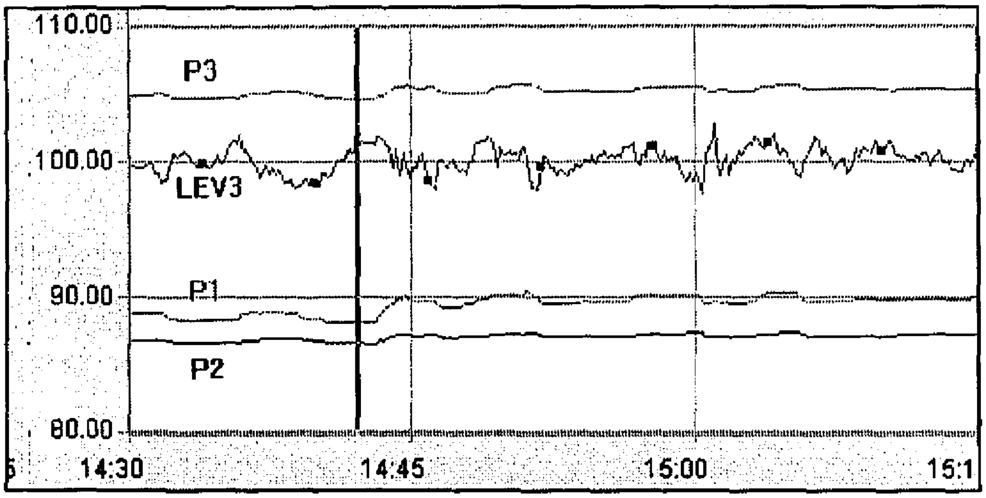


Figure 22.- PID, TC as M.V., Washwater disturbance

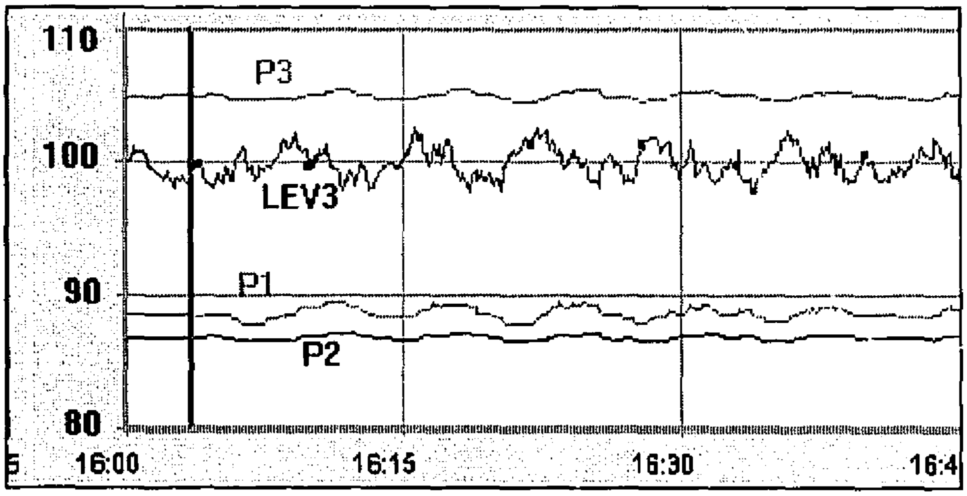


Figure 23.- PID, TC as M.V. Feed disturbance

Figure 23 corresponds to a feed disturbance. In this case J_f was changed from 0.40 to 0.46 cm/s. The response was quite similar to the disturbance produced by the washwater, with a slight oscillation in the pressure transducer readings.

5.4 Washwater as manipulated variable

In the Figure 24, the use of washwater as manipulated variable to control the level is presented. The main limitation is that the operational window or range of allowed level fluctuation due to this variable is reduced, because the system permits only a relatively small range of fluctuation in washwater flowrate inside which it is still possible to obtain froth overflow.

In real practice the slurry retention time should be kept as high as possible, in order to favour the collection of hydrophobic particles, so that washwater flowrate should not be too high. In current practice the washwater is never > 50% of the feed flowrate. On the other hand, in most applications, the bias should be positive to provide a good reduction of the entrainment of hydrophilic particles. A common approach is to use a washwater rate of about the same as the liquid rate in the overflow. Another consequence, at least in laboratory scale, was that low washwater flowrate increased froth coalescence and, below a certain limit, froth overflow was no longer possible.

This restriction in the range of washwater flowrates forces, in practice, the use of parallel measures, like the implementation of constant feed/underflow ratio, to help in applications where the washwater is manipulated to control the level [3].

The best set of parameter values for the PID controller, and the values calculated using the Cohen-Coon method, are given below:

	PB	τ_i	τ_d
Tuned	200	7.0	0.1
Cohen-Coon	458	9.5	1.5

As depicted in Figure 24, the level can be controlled, even when high changes in gas flowrate are imposed; however, the overshoot produced in the transients is high. As a consequence, in this application, some measures should be taken to avoid abrupt changes in operational parameters.

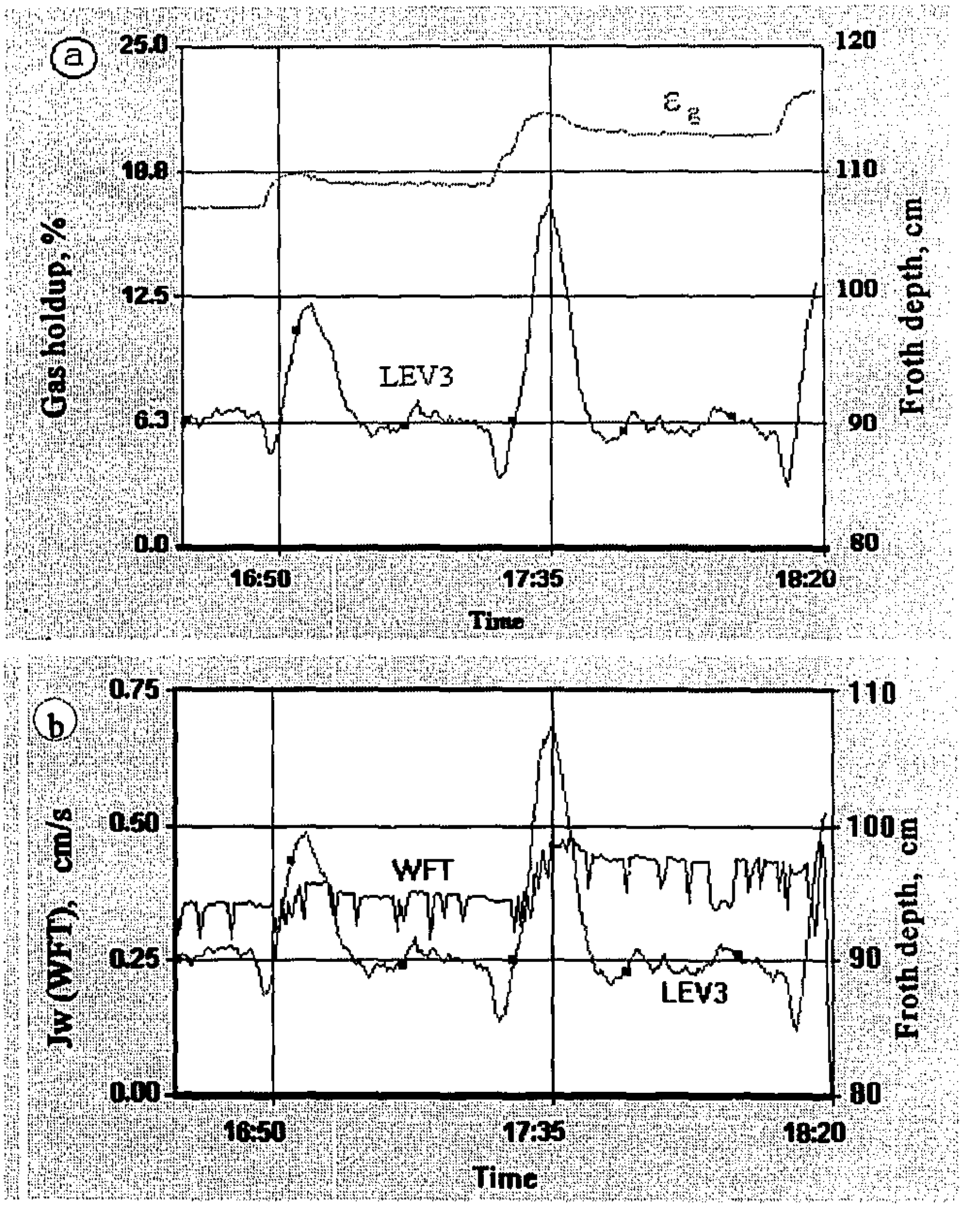


Figure 24.- PID, Washwater as M.V., air disturbance
a) Gas holdup - LEV3 b) Jw - LEV3 vs. time

In Figure 24 a and b, two incremental steps in air flowrate were executed, the first at 16:47 from Jg = 0.72 to Jg = 0.78 cm/s, and the second at 17:35 to Jg = 0.91 cm/s. An interesting effect of the increment in air flowrate on the calculated level LEV3, is that immediately after the step, the level is increased (froth depth is reduced), then the response is reversed, and the froth depth is increased far above the level set point, 90 cm in this case, finally falling again by the action of the controller, which increases the washwater flowrate (Figure 24b). In Figure 24a the gas holdup (ϵ_g) is included. This variable follows the increments in air flowrate, from ϵ_g = 17% to 18.2% in the first step and to 20.5 % in the second step.

The discontinuity in LEV3 and in WFT (set by the controller output) is due to an excessive gap or deadband (± 1 cm), used in the PID action during this test; softer transitions are produced with lower deadband values for the PID response.

5.5 Feed as manipulated variable.

Very few tests manipulating the feed were run to control the level. This is the least likely to be manipulated in a feedback level control loop; however, in certain situations it may be useful. The system response to manipulation of feed flowrate is quite similar to that of the underflow manipulations, so that there is no need to repeat the experiments run with underflow as manipulated variable.

Figure 31 (page 75), corresponds to a test where feed was used as manipulated variable. In this test the behaviour of equation LEV3, outside its valid range (h1--h2) was observed, with a constant ϵ_g. In this case, the use of underflow as manipulated variable is not advisable because of consequent changes in ϵ_g.

The response to the feed as manipulated variable was quite similar to that of the underflow, - steady-state was reached in a very short time after introducing steps in level set point, and, insignificant overshoot in transient state was observed.

CHAPTER 6 - RESULTS AND DISCUSSION, PART II

ACCURACY OF LEV3, COMPLEMENTARY TESTS.

The level estimates from triple pressure method (LEV3), were always different from the true level (determined by visual observation). This error was dependent on the operational parameters and also on the actual position of the level.

This error in LEV3 was assessed by executing a series of laboratory tests and from pressure profiling in an industrial flotation column.

At the end of this second part, results of complementary tests and pressure profile data are presented. This information was used to suggest some possible alternatives and solutions to problems related to the inverse response, or to expand the valid range of equation LEV3.

6.1 Error evaluation, LEV3 equation

To evaluate the error, a series of tests were run placing the true level in different positions so as to cover a range from ~ 20 cm below h2 up to 20 cm above h1, while maintaining all other variables constant. Beside this, tests were run to evaluate the effect of other parameters on the calculated level error, following the same procedure, to scan the whole valid range of the LEV3 equation.

Some tests were run in open loop, imposing level changes by small feed or washwater flowrate steps, but most of the tests were run in closed loop. In automatic mode, the feed was used as manipulated variable, changing the level set point in small increments. The true level was read only when a new steady-state was attained, taking note of the time, and data were retrieved from memory corresponding to the same moment the true readings were taken.

6.1.1 Results

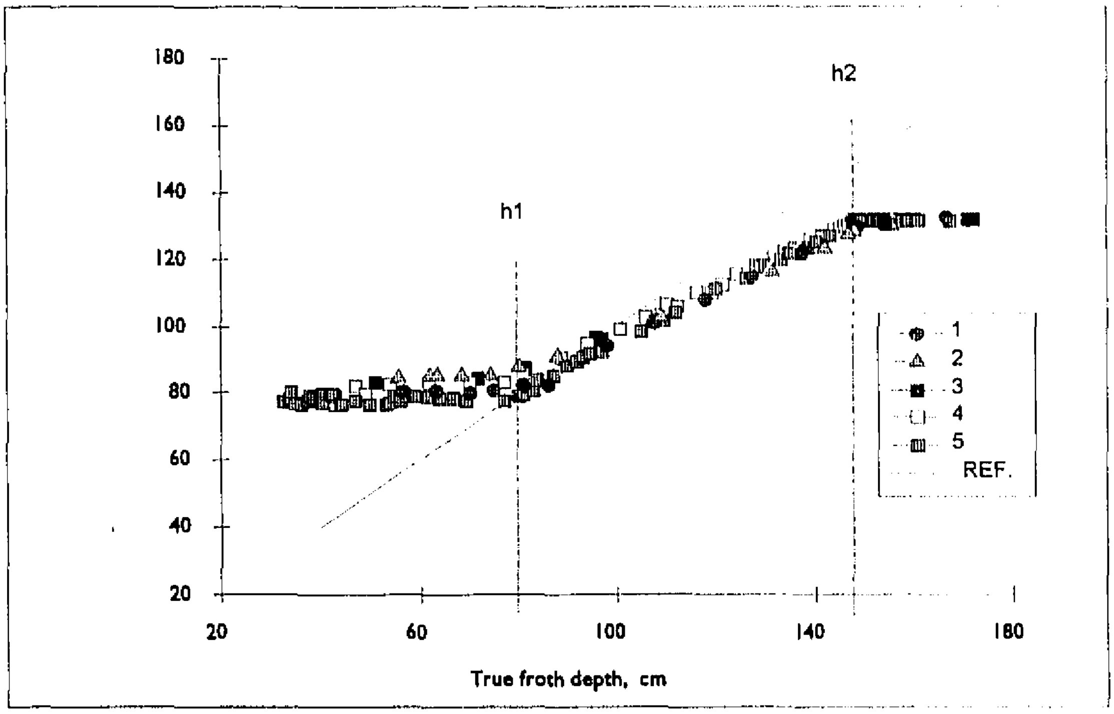


Figure 25.- LEV3 error evaluation, 5.7 cm x 4.0 m column

Table 8. Tests data for Figure 25

2.1/4" Mc Gill Froth/water 30 ppm

Sparger # 2 (2μ pores) Cross section = 25.5 cm^2

Test No.	Jg	Jw	Jf	Ju	ε_g	MODE
1	0.98	0.25	M.V.	0.55	16.8	Auto_T
2	0.88	0.22	M.V.	0.5	17.4	Auto_F
3	0.88	0.22	M.V.	0.5	16.1	Auto_F
4	0.98	0.15	0.36-0.35	0.5	16.6	manual
5	0.98	0.14	0.37-0.38	0.5	16.5	manual

Air-water tests were run in 5.7 cm x 4.0 m, 7.6 cm x 4.5 m and 6.3 cm x 6.5 m laboratory columns. The location of the transducers for the three columns are given in Figure 12 (page 36).

A typical set of results for tests run in the 5.7 cm column is presented in Figure 25.

In order to evaluate the error, the calculated level from LEV3 was plotted as a function of true level, and three reference lines were included: The true level reference line (1:1, or 45° line), the h1 and h2 position line (vertical dotted lines).

In Figure 25 it can be seen that the highest accuracy is produced when the interface is close to h1. In fact, the calculated level equals the true level at this point as there is no

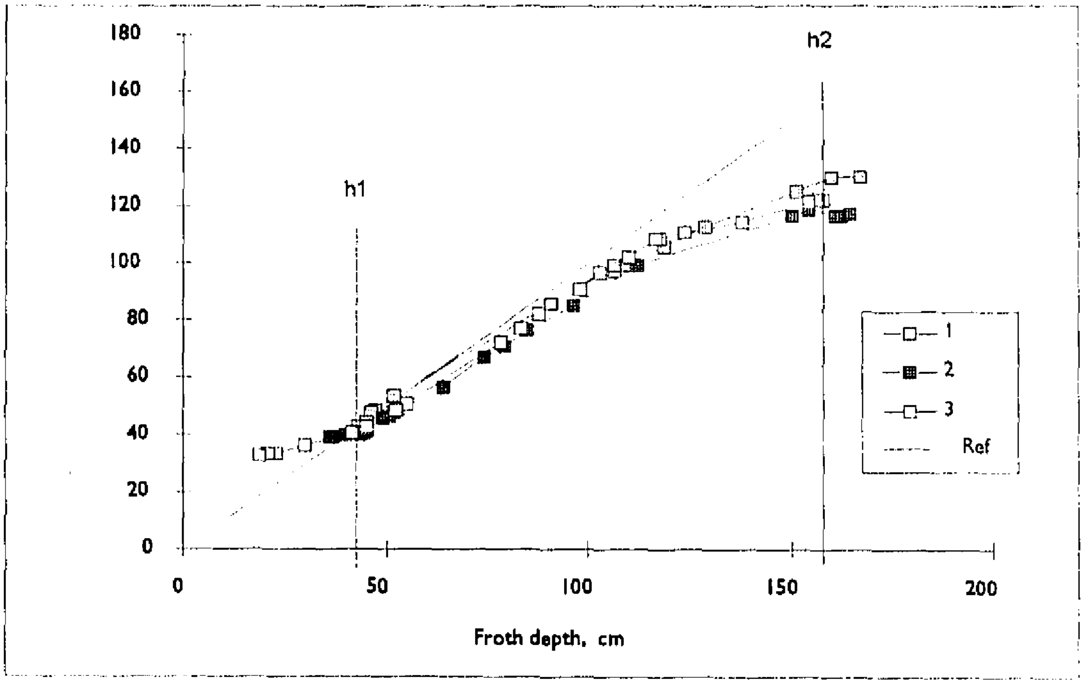


Figure 26.- LEV3 error evaluation, 7.6 cm x 4.5 m column

Table 9. Test data, for Figure 26

Sparger # 3 (5μ pores) Froth/water 30 ppm

Cross section = 44.77 cm^2 Mode: Manual

Test No.	Jg	Jw(i)	Jw(f)	Ju	Jf	ϵ_g
1	1.00	0.75	0.28	0.55	0.52	24.0
2	0.89	0.10	0.28	0.55	0.50	19.3
3	0.78	0.20	0.35	0.55	0.37	18.1

uncertainty in the froth zone density (this point is pursued later). For levels above h1, LEV3 is no longer sensitive to level changes yielding a constant value approximately equal to h1. In the range h1 to h2, as the level goes down, an increasingly negative error is produced, i.e. the calculated froth depth is less than the true depth. Below h2, the equation is again no longer sensitive to changes in level, and once more yields a constant value.

The tests in Figure 26 on the 7.6 cm x 4.5 m column were run manually in open loop, with all variables set within normal ranges. The main concern was to ensure positive bias and froth overflow to simulate normal column operation.

Figures 25 and 26 show the same behaviour in both columns (7.6 cm and 5.7 cm).

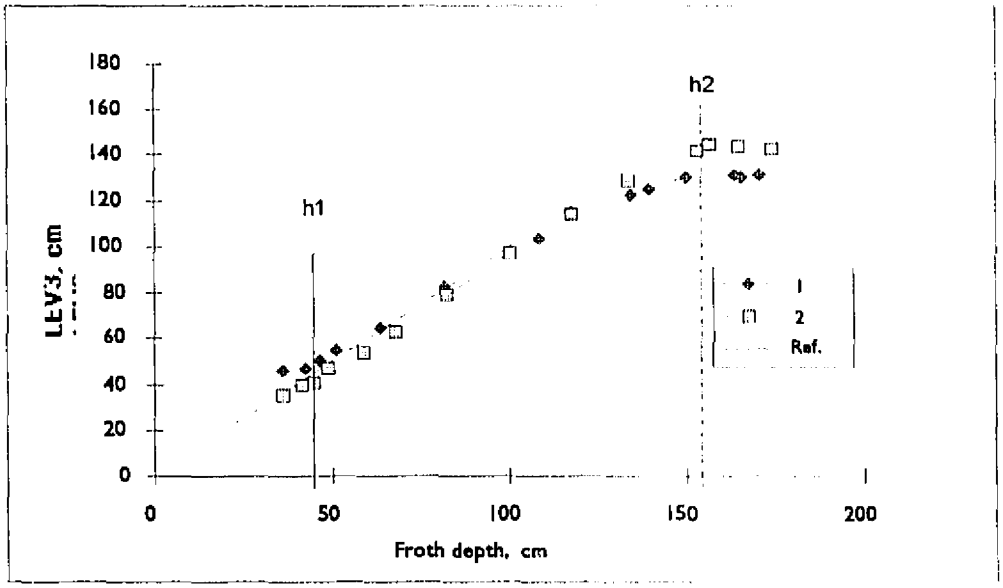


Figure 27.- LEV3 error evaluation, 7.6 cm x 4.5 m, high Jg

Table 10. Test data for Figure 27

Froth/water 30 ppm Cross section = 44.77 cm^2

Sparger #3 (5μ pores) Mode: AUTO_F

Test No.	Jg	Jw	Jt	Jf	ϵ_g
1	1.71	0.04	0.10	MV	22.7
2	1.71	0.20	0.55	MV	28.0

In the tests in Figure 27, the effect of high (relatively) gas flowrate was studied. The column was set to the maximum Jg (= 1.71 cm/s) at which the level can still be detected visually (higher values producing churn-turbulent conditions where the interface position is no longer visible). The main difference from the previous tests is that the error or difference between the calculated LEV3 value and the true level, is significantly reduced between h1 and h2, giving practically superimposed curves. Outside of h1 and h2, however, LEV3 was again insensitive to the true level.

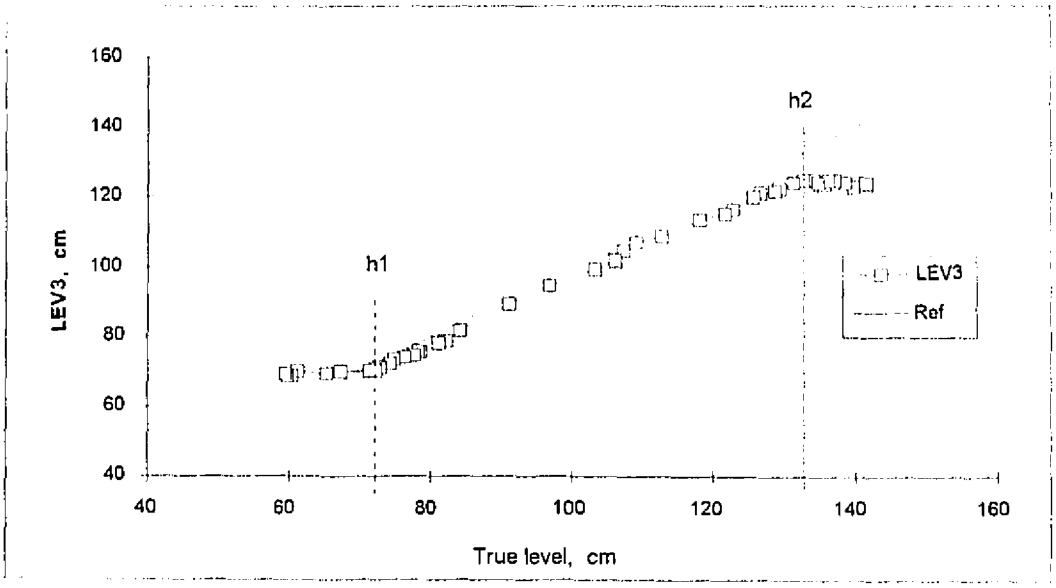


Figure 28.- LEV3 error evaluation, 6.3 cm x 6.5 m column (CANMET)

Table 11. Test data for Figure 28

Froth/water 20 ppm — Cross sect. 31.7 cm^2

Sparger # 3 (5μ pores) — h2: 132.7 cm h1: 72.2 cm

Jg	**Ju**	**Jw**	ϵ_g	**MODE**
1.58	0.82	0.23	22.0	AUTO_F

In Figure 28, results of the same type of test run at CANMET, Ottawa are presented. In this case, the error is also relatively small compared with the previous results, which may reflect again the high gas rate.

In the next section, pressure profile data are presented. This information will be used in the analysis of the LEV3 equation error and also to evaluate the effect of different positions of P1 and P2 on LEV3.

6.2 Pressure profile of an industrial column

Figure 29 shows data on pressure readings and the calculated density over 50 cm increments along column # 4, Matte plant, INCO, Sudbury (test gh04, November 1993). In this Figure, the calculated bulk density (ρ_l) inside the collection zone is fairly constant. This is not the case for the froth zone. From this profile we can infer that the interface is in the range 3.5 -- 4 m. from the top, which was confirmed with a single point conductivity probe, which detected the level at 3.7 m. However, on the monitor oif the control room the reported level was: ~75.0" (1.9 m), i.e. an error of ~1.8 m, errors of this magnitude are the general

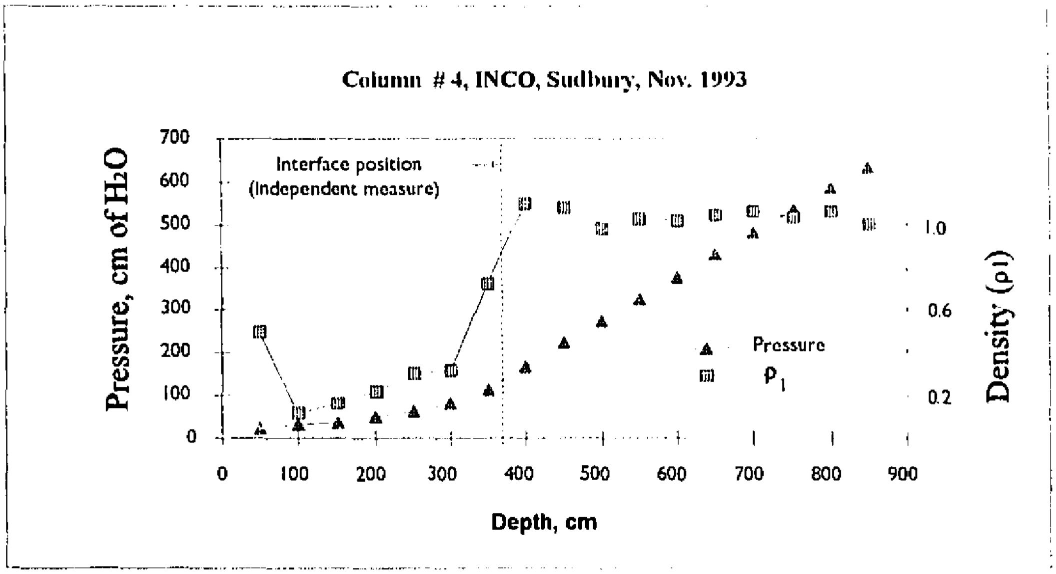


Figure 29.- Industrial column, pressure profile

case and has been noted before[10, 11].

6.3 Analysis of LEV3 error tests

When the interface is placed between h1 and h2, which is the valid range for LEV3, all the terms except P2 are relatively constant under steady condition. The ratio (P3-P2)/(h3-h2) in the equation LEV3 represents the collection zone density which remains constant, while P1/h1 represents the froth density which changes only slightly due to fluctuations in level. Hence, LEV3 is a function of only P2. When the level moves this produces a change in P2, and LEV3 is able to follow, or is sensitive, to changes in the interface position in this range.

The error in calculated level, inside the range h1--h2, is produced mainly by the difference between the estimated froth density (P1/h1), and the true froth density. The true froth density (from the interface to the top of the column), is higher than the density of the froth above P1 to the top of the column; that is P1/h1 underestimates the true froth density. This can be easily verified using the pressure profile of Figure 29, and from laboratory data.

To illustrate the difference in estimated and true froth density, some laboratory column data is presented in Table 12.

Table 12. Estimated and true froth density, laboratory column

Column size: 5.7 cm x 4 m System: Air/water

Flowrates (cm/s): Jg = 1 Jw = 0.15 Jf = 0.35 Ju = 0.5

True level	**P3**	**P2**	**P1**	ρ_f	ρ_f(est)	ρ_c
(cm)		(cm of H_2O)		P2/h2	P1/h1	
148 (on P2)	239.4	66.6	31.4	0.45	0.40	0.80

This difference is confirmed by the data taken from the pressure profile(Figure 29) and presented in Table 13.

Table 13. Estimated and true froth density, industrial column

Column # 4 Matte Plant, INCO, Sudbury System: Air/slurry

Test gh04 Assuming: $h1 = 100$ cm , $h2 = 375$ cm, $h3 = 800$ cm

True level (cm)	**P3**	**P2** (cm of H_2O)	**P1**	ρ_f P2/h2	ρ_f(est) P1/h1	ρ_c
375	588.6	142.8	31.7	0.38	0.32	1.05

Replacing these values in equation 3 (LEV3), Table 14 shows that the calculated froth depth using the estimated froth density, is smaller than the one using true density. This is confirmed by the pressure profile data (Figure 29) which shows that any estimate of froth density taken above the interface will be lower than the true average froth density (i.e. from the interface up). The magnitude of this error will depend on the distance between P1 tap point (h1) and the interface, and also on operating conditions which alter the pressure profile; this error inside the valid range will reduce as the interface rises to approach the position of P1; at P1, the true and estimated density are momentarily equal and LEV3 is precise.

Table 14. LEV3 values using estimate and true froth density

	Laboratory	**Industrial**
Estimated ρ_f	131.5 cm	343.8 cm
True ρ_f	150.3 cm	374.6 cm

When the interface is placed below h2, LEV3 is no longer sensitive to level changes. Any fluctuation in level will reflect only minor changes in P2 and in the ratio P1/h1, because both sensors (P2 and P1) in this case are in the froth zone, and will sense only changes in froth density, which are relatively small compared with the changes in pressure produced by changes in level. P3 is the only transducer subject to changes in level, and determines the term (P3 -P2)/(h3 -h2) which no longer represent the collection zone density because of the presence of the froth layer between P2 and the interface.

To analyze the response of LEV3, data when the interface in *on* P2 is used, and then by simulation, the froth depth is estimated assuming that the true level is at 10 cm and 20 cm below P2.

Taking data from an experiment in the 5.7 cm column with level on h2 in steady-state:

h1 (cm)	h2 (cm)	h3 (cm)	P1	P2 (cm of H2O)	P3	ρ_f	ρ_c	ρ_f(est.) P1/h1
78	149	365	33.47	71.16	249.51	0.478	0.826	0.429

a) Level on h2 LEV3 = (149*0.826 - 71.16)/(0.826 - 0.429)

LEV3 = 130.7 cm True level = 149 cm

b) Level 10 cm below h2

Assuming that the true froth density does not change, the only term in LEV3 that changes is the ratio (P3-P2)/(h3-h2). In fact the only variable would be P3, because it is the only sensor able to follow the change in level

P3 = 206*0.826 + 159*0.478 = 246.16 cm of H2O

(P3-P2)/(h3-h2) = 0.81 LEV3 = (149*0.81 - 71.16) / (0.81 - 0.429)

LEV3 = 130.0 cm Simulated froth depth = 159 cm (i.e. h2 + 10)

c) Level 20 cm below h2

P3 = 196*0.826 + 169*0.478 = 242.68 cm of H2O

(P3-P2)/(h3-h2) = 0.794 LEV3 = (149*0.794 - 71.16) / (0.794 - 0.429)

LEV3 = 129.2 cm Simulated froth depth = 169 cm (i.e. h2 + 20)

These results confirm that the calculated froth depth, when the interface is below h2, is no longer sensitive to changes in level.

On the other hand, when the interface is on or above h1, P1 and P2 are sensitive to interface displacements. However, both change by the same amount for a given change in level, and compensate for each other so that the value of LEV3 remains constant and equal to h1, for any level position above h1. This can be proved by the following calculation:

> As in the previous analysis, the density of the collection zone remains constant. The relation between P2 and P1 when the level is above h1 is given by:
>
> $P2 = P1 + \rho_c(h2 - h1)$, where $\rho_c = (P3 - P2)/(h3 - h2)$
>
> Replacing in equation (3):
>
> $LEV3 = [h2\rho_c - (P1 + h2\,\rho_c - h1\rho_c)]/[\,\rho_c - P1/h1]$
>
> Simplifying: $LEV3 = h1$

Meaning that for any position of the interface above h1, LEV3 is always equal to h1.

Finally it is observed that for high air flowrate and underflow flowrate (test 2, Figure 27, page 67), which determine a high gas holdup, the error is considerably reduced. This suggests that the froth density is more uniform under these conditions, i.e. there is no pronounced froth density profile.

6.4 Importance of LEV3 error in practical applications

The magnitude of the error introduced by LEV3 may not represent a significant problem in industrial applications, provided the actual level is inside the valid range; however, if the level is below or above this range, the magnitude of the error increases and the operator will not be aware that the level may be far from that reported.

If the system were using the LEV3 data to automatically control the level, then potential disaster looms as level displayed in the control room may appear as a nicely constant steady-state value, while in reality the column could be in the extreme have pulp overflowing or be full of froth. This maybe the reason some operators prefer to use only one pressure transducer, placed close to the bottom of the column, to control the level, instead of the triple pressure method. The use of one transducer, though being less accurate, avoids the extreme conditions mentioned above. As a complement to the level control study, some experiments were done in order to try to detect and avoid the "out-of-valid-range" condition, and also to explore the use of some algorithms to monitor this condition and switch the system to use alternative level estimate equations rather than using LEV3 exclusively.

6.4.1 Limitations of LEV3 equation in control loops.

Beside the problems related to the out-of-valid-range condition, another problem related to the use of the LEV3 equation in feedback control loops was observed:

Figure 30 shows that when a step in washwater occurs, the change in froth depth is initially in the reverse direction compared to the eventual response. This is known as an inverse response, and if the variable that generates this inverse response is used as manipulated variable, the controller action is likely to produce oscillations in the controlled variable, and possibly may lead to loss of control. Even if washwater were changed for other

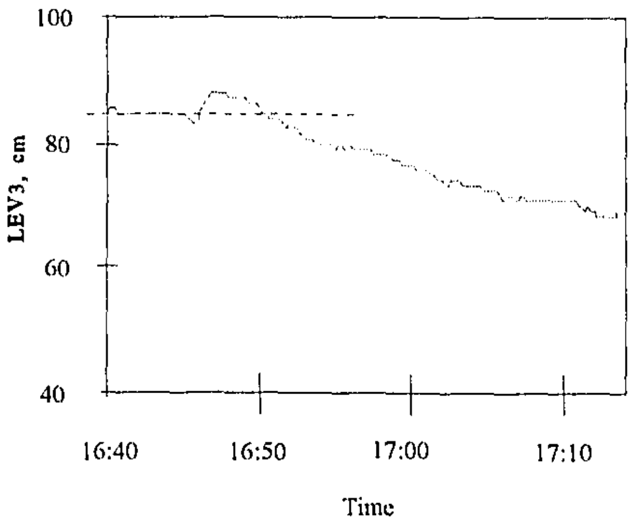


Figure 30. Inverse response of LEV3, washwater step (from Fig. 14-b)

reason, e.g. in a grade control strategy, adverse effects on level control may occur.

The initial inverse response is due to froth density changes, interpreted by LEV3 as level changes, as explained in section 5.1.1, page 49.

In the following section, tests run to evaluate the behaviour of LEV2 and LEV3 outside the range h2--h1 are presented, as well as some data related to the effect on LEV3 of different positions of the P1 and P2 tapping points.

6.5 Complementary tests and data

6.5.1 Response of LEV2 and LEV3, level above h1

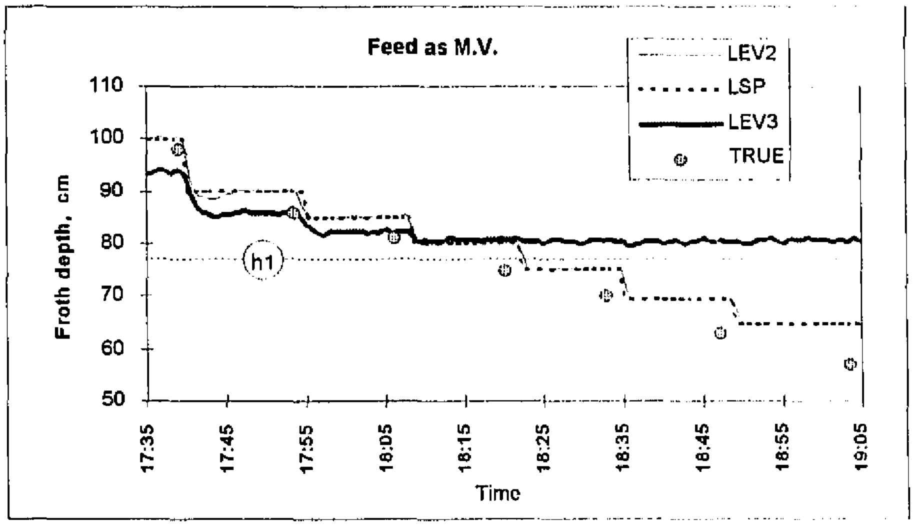


Figure 31. Response of LEV2 and LEV3 to steps in LSP

Table 15. Test data for Figure 31

Column size: 5.7 cm x 4 m   Feed as manipulated variable

h1 (cm)	**h2** (cm)	J_u (cm/s)	J_g (cm/s)	J_w (cm/s)	ϵ_g (%)	ρ_f (est.)	**Mode**
77	148	0.55	0.98	0.25	19.5	0.38	AUTO_F

Figure 31 corresponds to a test run in closed loop, using feed as manipulated variable, and equation LEV2 to calculate the froth depth in the control loop. In equation LEV2 a value of 0.38 was assigned to the froth zone density, this value corresponds to the ratio P1/h1, when the true froth depth was ~ 100 cm.

This figure covers the range: ~20 cm below h1 to ~20 above h1. As we can see LEV3 follows the changes in level only when the true level is below h1 (froth depth greater than h1), while LEV2 is sensitive to changes in level over the entire range.

As a pressure transducer can effectively follow changes in level (pressure) occurring only above its position, the apparent valid range of LEV2 is from h2 to the top of the column. The top limit of the valid range is confirmed by Figure 31; however, the lower limit extends a little below h2 as shown in Figure 32.

6.5.2 Response of LEV2 and LEV3, level below h2

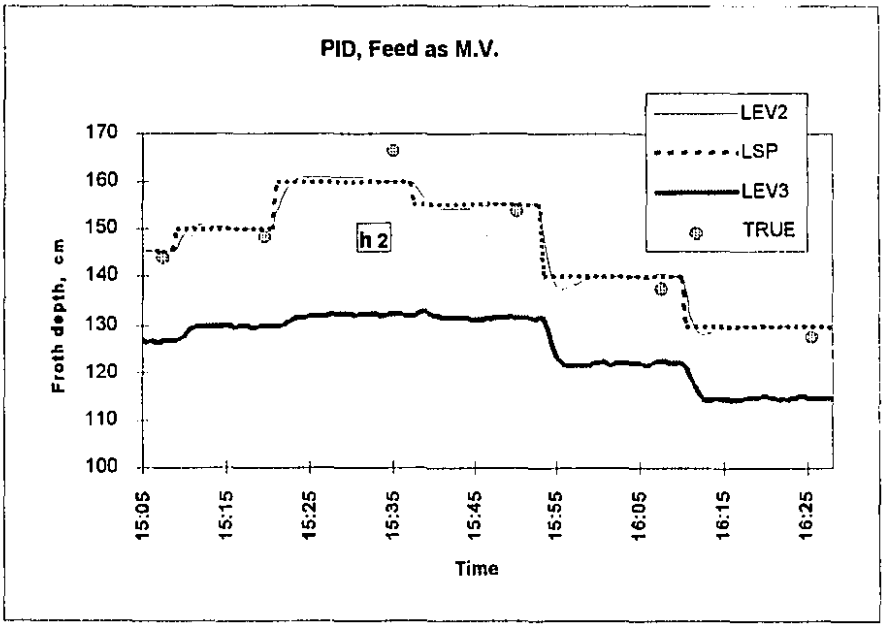


Figure 32. Response of LEV2 and LEV3, to steps is LSP (level below h2)
(Test data was the same than those in Table 14)

Figure 32 covers the range: ~20 cm below h2 to ~20 above h2. In this last test, after the level goes below h2 at time ~ 15:22, LEV3 is no longer sensitive to changes in level until the level goes again above h2 at ~ 15:44. Though LEV2 become much less sensitive, it still follows changes in level down to, at least, 15 cm below h2 .

6.5.3 Effect of h1 and h2 positions on LEV3 error

In Figure 33, using the data in Figure 29 (pressure profile, page 69), level from LEV3 was calculated as a function of h2 for 3 positions of h1. The result shows that the error in LEV3 is reduced by lowering h2 until reaching the depth of 3.5 m, thereafter, the error remains constant apparently without penalty. Clearly the valid range of LEV3 has been greatly increased.

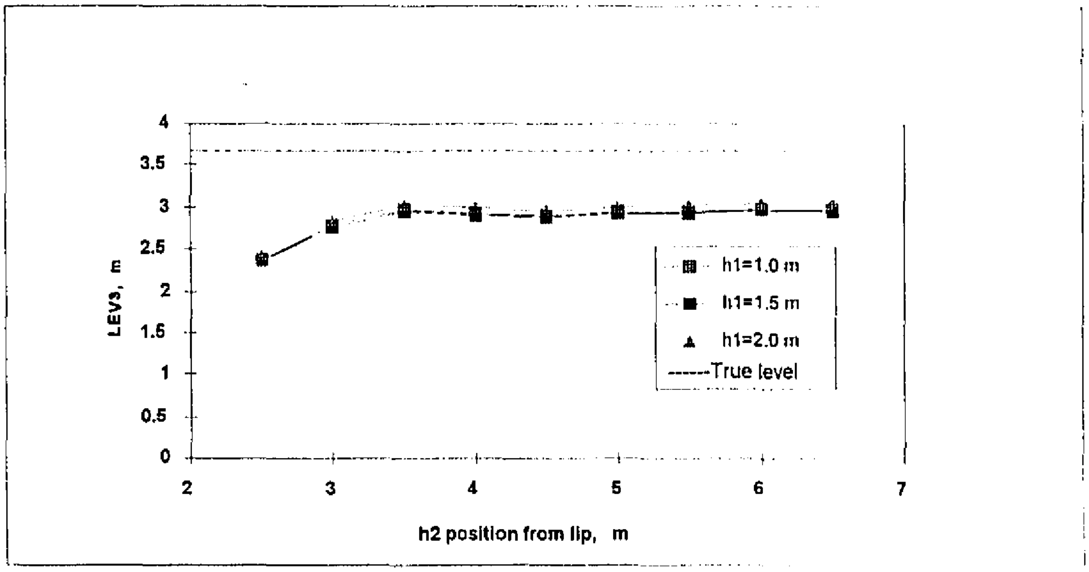


Figure 33.- Effect of h2 and h1 position on LEV3

The question now is: How close to each other can P3 and P2 be installed without affecting the term representing the collection zone density in LEV3 ?

6.5.4 Collection zone density for different positions of h2

From the data of test gh04, Figure 29, the values of the calculated collection zone density are presented in Figure 34, as a function of the distance between P3 and P2, and assuming 2 positions for P3: 8.5 and 8.0 m from the top of the column.

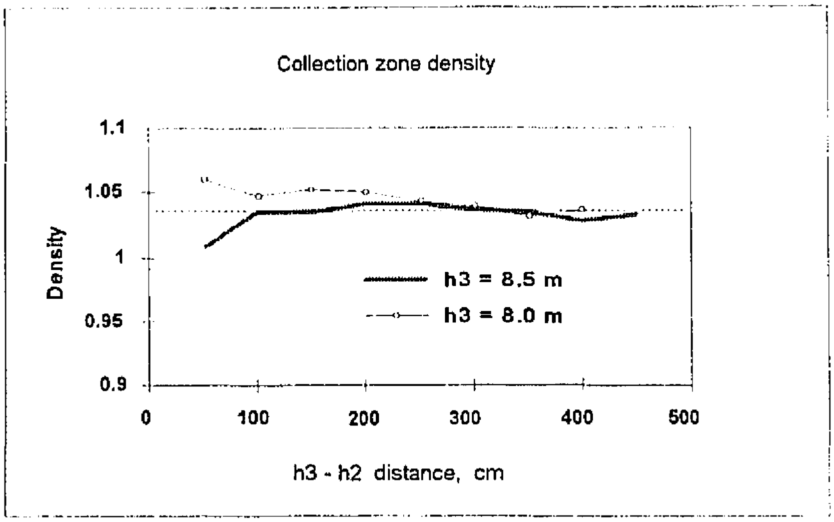


Figure 34. Effect of h3-h2 distance on the calculated ρ_c

In this figure, the values of density for a distance of 1 m or higher do not deviate greatly from the average value of 1.035 (taken for a separation of 4.5 m). The maximum difference is obtained for a distance of 50 cm in which the density goes down to 1.01 in one case and up to 1.06 in the other.

In Figure 35 the deterioration of the calculated density, when P2 approaches P3, is shown more clearly. In this figure the density of the slurry, for the same data of Figure 29, is calculated for consecutive readings of pressure with separations of 50, 150, 200, 250 and 300 cm, and assuming that P2 and P3 are displaced from the bottom position (8.5 m), up to the position of 5.5 m .

The points obtained for 50 cm, are the most dispersed from the average value. To evaluate the deterioration, LEV3 has been calculated and compared with the value obtained with the average slurry density (1.035). A deviation of 5.6 cm in LEV3 was found corresponding to the highest deviation in density.

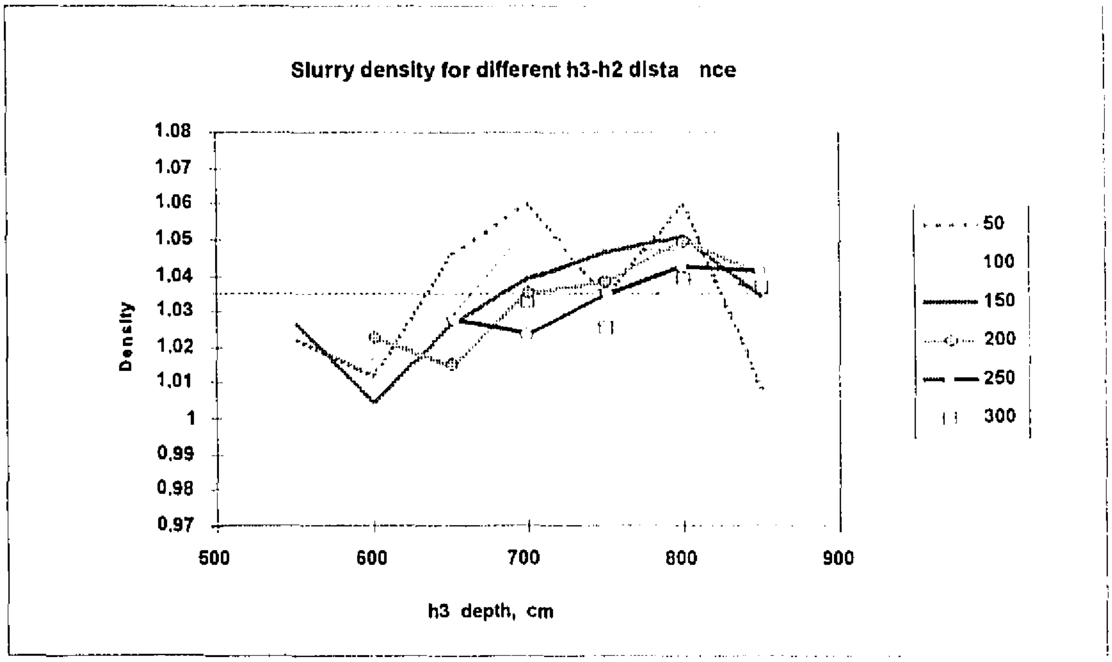


Figure 35. Effect of h3-h2 distance on ρ_c for various h3 depths

CHAPTER 7 - CONCLUSIONS AND SUGGESTIONS

7.1 Hardware and software

The instruments selected suited the system very well. The Bailey pressure transducers proved to be flexible, easy to calibrate and define ranges, and gave stable readings. It was not necessary to recalibrate the instruments during the execution of the project.

Another reliable instrument was the air mass flowmeter/controller, which was able to accurately set the air flowrate in less than one second, even for a full scale step change. The only problem arose when liquid flowed back into the instrument.

The input/output board OPTO-22 and the software FIX_DMACS, proved to be of sufficient quality and capacity to accomplish the tasks required and the technical support of both suppliers was good. The same was also true of the suppliers of the pressure transducers, BAILEY and the mass gas meter/controller, MKS.

The software configuration gave no major problems, in executing the automation and stabilizing level control applications.

Analog input blocks could filter the input signals noise over a customer-selected range from 0 to 15, yielding clean, smooth records. However, a software-created delay in the instrument readings is produced which, according to the filtering degree, may create long delays, unnecessarily damping the controller response. Consequently, it is advisable to use low filtering or none at all.

A limitation in the FIX-DMACS version used was that the capacity in bytes per database was limited to 64 K, and there were no warning prompts written in the program to indicate when this limit is reached. However in Distributed Control Systems (DCS), for which FIX-DMACS is oriented, these are unlikely to require even this size of database.

Another factor to be aware of is related to the deadband of the PID response which should be kept lower than ~ 0.2 cm. The use of deadbands in the order of 1 to 2 cm has the advantage of reducing the frequency of changes in the manipulated variable but, even if this gap may not be important from the performance point of view, a cumulative effect is produced, and when the level moves outside the deadband, the manipulated variable changes in large steps, instead of the small frequent steps when a small deadband is set. As a consequence, oscillation is induced in the system, which is undesirable. When the deadband is high, the recorded calculated level has a typical "saw tooth" shape (Figures: 21, 22 and 23).

7.2 Problems related to the feedback control loop

The parameter values obtained using the Cohen-Coon method, though yielding stable conditions in the system, needed to be tuned, because of the coupled effect of the initial jump in the controller output when the system is switched to automatic from manual, and the narrow band represented by the valid range of the LEV3 equation. The valid range of an equation is defined here as the range in which changes in level can be sensed or followed by the equation.

Manipulation of the initial parameter values was relatively easy targeting the following criteria: low overshoot, reach new steady-state in minimum time, soft manipulation of the controller output, and low oscillation of the system in the new steady-state.

In relation to the type of control, PID appears to be the best compared to P and PI controllers, again because of the initial jump in the manipulated variable, and narrow band of allowed level fluctuation.

7.2.1 Manipulated variable

From the open loop response tests, due to the inverse response and relatively long delay, air flowrate can not be used as manipulated variable (at least not in simple feedback control loops). In practice gas rate is never used for this task, however, it is frequently changed for optimizing grade/recovery control and, therefore, effects on level will occur.

The response to a step change in washwater was typified as "false inverse response" because the inverse response is produced only in the calculated value LEV3 not in the true level nor in the values of LEV2 and LEV1. In these two last equations, a first order with time delay response was obtained, thus the use of washwater as manipulated variable is possible if LEV3 is replaced by either of the other two equations.

Underflow and feed step changes, generated first order responseswith relatively short time delay in open loop tests, and thus can be advantageously used as manipulated variables. However, as feed is set by external constraints, it is the least likely to be used for this purpose in practice; this variable may be used in some laboratory tests.

7.3 LEV3 error, cause and consequences

The error in the calculated level is produced mainly by the difference between the estimated froth density (P1/h1) and the actual froth density (from the interface position to the top of the column). This error is a function of the distance between P1 and the interface; however, above a given distance the change in error becomes insignificant. Apparently at a given distance from the interface, the froth density becomes constant.

The error is zero when the interface is on h1, and if some difference between the calculated and true level exists, it can be attributed to inaccuracy or miscalibration of the sensors.

The positions h2 and h1, are the limits of the valid range of application of LEV3. Inside this range the equation is sensitive to changes in level.

For the present experimental conditions, it was found that the maximum error was ~ 30 cm (or about 20% of froth depth) when the true level was inside the valid range and reduced at high gas rates. The status "level-above-h1" can be determined, because LEV3 always yields a value equal to h1 when the true level is above h1. To account for inaccuracies in the system, a safety factor may have to be introduced to avoid incorrect level information. However, this factor will be limited to the range of operating parameters over which the factor was established.

In the case where the interface is below h1, the ratio P1/h1 gives an underestimation of the froth density yielding an error which will depend not only on the relative position of the interface and h1 (longer the distance greater the error), but also on the operating conditions (any parameter that affects froth density will affect the error).

The worst situation occurs when the interface is below h2. In this case, not only is the error high, but the calculated level will appear constant, so that operators may conclude that they have a stabilized condition while reality may be far from this. Attempts to find a way to detect on-line this "below h2" condition, using pressure readings have thus far failed. However, some alternative solutions will be proposed.

7.4 LEV3 valid range limitation

A problem related to use of the LEV3 equation is its limited valid range of application. One alternative is to use LEV2 which has a wider valid range (from h2 to the top of the column). Even with the penalty of lower accuracy and the need to independently estimate the froth density, LEV2 can be used advantageously in some situations.

The use of LEV2 in feedback control loops, should include periodic updating of estimated froth zone density values perhaps using P1/h1, to prevent the error in calculated level from increasing over time.

The LEV1 equation has an even wider valid range, from h3 to the top of the column. However, its lack of ability to measure the collection zone density, represents a great handicap in relation to LEV2 and LEV3. The problems using LEV1 have been well documented[7] and need not be considered further here.

7.5 Enhancing the valid range of LEV3

As stated, the main problem in the use of LEV3 for control is the possibility that the level is outside the valid range. One approach, therefore, is to find some means of avoiding the "out-of-valid-range" condition, either enlarging the range or signalling when the condition is encountered, so that the operator can correct the system, and drive the level back into the valid range.

The conclusions from Figure 33 (page 77), are:

- h1 position does not affect LEV3 (when the distance between h1 and the interface is ~ 1.5 m or higher). This is irrelevant in normal operation where h1 is ussually ~ 50 cm and the froth depth is smaller than 1.5 m.
- LEV3 is independent of h2, provided h2 is <u>below</u> the actual level. This is a consequence of the apparently constant bulk density in the collection zone.

Hence, lowering h2 effectively increases the LEV3 valid range. But, to keep the noise inherent in collection zone density calculation inside acceptable limits, from Figure 34 and 35, h3 - h2 > 1 m. This is coincident with previous work[1] on noise in density calculations from pressure signals.

With this information, we can conclude that the 3 pressure transducer should be placed as depicted in Figure 36, increasing the valid range (and avoiding disturbances induced by the incoming feed stream on P2 readings).

7.6 Signalling the "out-of-valid-range"status

The author was not able to signal on-line the "out-of-valid-range" (above P1 or below P2) status by simply using pressure transducers readings, with the system in steady-state. However, a procedure was applied to recognize the "below P2" or "above P1" status, by inducing a level step change of ~ 10 cm, while monitoring equations LEV1 and LEV3. If the actual level is below P2 or above P1, LEV3 will not show any change, while LEV1 will change proportionally to the level step. Of course if the actual level is close to a given pressure transducer tap, the response may be masked, but this can be avoided by executing two consecutive step-ups, followed by a step-down. With this procedure the actual status becomes clear.

When the system is in dynamic or transient state where the level is continuously changing, it is easy to determine when the actual level crosses the h2 position by comparing LEV1 or LEV2 with LEV3, since at that point LEV3 become constant, while the other two equations will continue to change following the true level change. In the same way, the condition "above P1" can be detected as shown in Figure 17 (page 53), where before 12:01:30 and after 12:21:30 true level was in this condition.

7.7 Washwater as manipulated variable

The manipulation of underflow to control level is relatively simple and does not require special consideration.

The use of washwater as manipulated variable is favoured in some industrial practice[2,3] because it is a stream that is easy to handle (just being water). The inverse response of LEV3 to a step change in washwater represents a major problem which could be solved by replacing this equation with LEV2, which does not produce an inverse response.

The response of the level to manipulations in the washwater stream is quite slow, due to the damping action of the froth. For this reason it is successful in controlling only slow disturbances (as apparently encountered in industrial scale flotation) but it can not handle fast disturbances like those generated by fluctuations in the feed stream. That is why the manipulation of washwater to control the level is complemented with a constant feed/underflow flowrate ratio or difference.

7.8 Control alternative, separate control line

Besides the problem of the inverse response in LEV3, the use of washwater as manipulated variable has the inconvenience of the relatively high time delay due to the nature of the froth. The long delay, ~5 minutes, that it takes for the washwater to cross the froth and reach the interface represents an important drawback to the use of this stream in level control.

One way to take advantage of the washwater and avoid the inverse response and the long delay produced by the froth, is to install a separate control line, as depicted in Figure 36. This control line would be the manipulated variable and may use the same washwater fluid.

7.9 Summary of solutions proposed

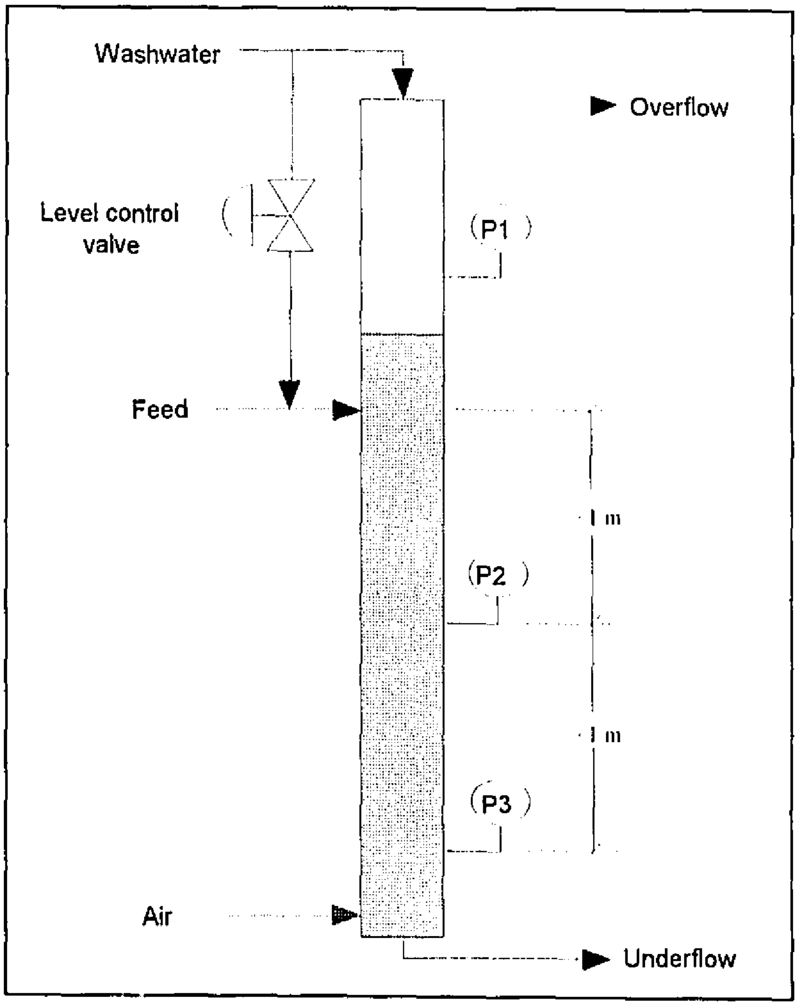


Figure 36.- Additional control line, new P2 position

7.9.1 Install P2 midway between Feed and P3 taps.

Figure 36, presents a possible solution to avoid the condition "interface below h2": The installation of P2 further down the column compared to current practice. This has the following advantages:

- Reduce disturbances generated by proximity of the feed inlet.
- Increase the valid range of LEV3.

7.9.2 Install a separate control line

An independent separate control line installed as depicted in Figure 36 or through a separate tap at the same height of the feed inlet point, has the following advantages:

- Avoids the inverse response of LEV3, when washwater is used as manipulated variable (froth density will not be affected by the controller action).
- Reduces considerably the time delay response of the system, by bypassing the froth.

7.9.3 Use of LEV2 instead of LEV3 in the control loop

This avoids the inverse response of LEV3 when washwater is used as manipulated variable. Despite introducing a higher error, improved stabilizing level control could be achieved. To further reduce the error, a correction for the froth density can be made, using average values from readings of P1 and P2 and updating LEV2 each ~10 minutes, or so.

7.10 Further work

As a complement to this project, and to determine if the proposed solutions are feasible the following tests are recommended:

a) Determine which is the minimum froth column above P1 to yield a valid or usuable froth density.

b) Study the effect of lowering P2, on accuracy and repeatability of level calculation; also, examine constancy of collection zone bulk density in industrial columns (on which the lowering of P2 is predicated).

c) Level control tests using slurries: Determine if it is necessary to retune PID parameters again.

d) Find if PID parameters tuned in laboratory column can be used directly at industrial scale.

e) Identify the nature of disturbances in industrial columns.

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APPENDIX 1

Summarized block data, from File auto.pdb

```
Tag      Type   I/O     Sca stat. Sc.time Cur. valu Description
----     --     ---     ---       ---     ---       --------

AFT      AI     B2:09   ON        2       0         Air Flowrate tramsmitter
FFT      AI     B2:05   ON        2       0         Feed Florate transmitter
P1       AI     B2:00   ON        2       0         Top pressure meter
P2       AI     B2:01   ON        2       0.4       Middle Pressure meter
P3       AI     B2:02   ON        2       257       Bottom Pressure meter
SAI_SET  AI     2       ON        2       ???       Simulated analog input
SAI_T    AI     1       ON        2       0         Simulated analog input
SAI_W    AI     0       ON        2       0         Simulated analog input
WFT      AI     B2:04   ON        2       0         W.W. Florate meter

AC       AO     B2:08   ON        ---     0         Air Controller
FC       AO     B2:11   ON        ---     4         Feed Controller
TC       AO     B2:12   ON        ---     4         Tailings Controller
WC       AO     B2:10   ON        ---     4         Wash water controller

DEN      CA     ---     ON        ---     1         Density (Collec.-h2)
DERIV    CA     ---     ON        ---     -20       Deriv [Dlev1/Dden]
GHU      CA     ---     ON        ---     0         Gasholdup (h3-->h2)
GHU2     CA     ---     ON        ---     99        Gasholdup (h2-->h1)
LEV1     CA     ---     ON        ---     172       Calculed level 1 PTx
LEV2     CA     ---     ON        ---     180       Calculed level 2 PTx
LEV3     CA     ---     ON        ---     152       Calculed level 3 PTx
RATIO    CA     ---     ON        ---     0         Ratio [Dlev1/ Dghu]

SV_A     DO     B1:00   ON        ---     OPE       Solenoid valve, On/off air
MOF      DO     B1:01   ON        ---     OPE       Manual operation flag
AOF      DO     B1:02   ON        ---     CLO       Automatic Operat. flag
TIV      DO     B1:03   ON        ---     OPE       Toggle top isol.valve
BIV      DO     B1:04   ON        ---     OPE       Toggle bottom isol.valve

DT_DEN   DT     ---     ON        ---     1         Delay DEN output
DT_GHU   DT     ---     ON        ---     0         Delay GHU output
DT_LEV1  DT     ---     ON        ---     172       Delay LEV1 output

EVA_P3   EV     ---     ON        ---     ---       Evaluate P3, and run pgstop

FAN_LEV  FN     ---     ON        ---     ---       Fanout calculated level
FAN_SET  FN     ---     ON        ---     ---       Fanout level set point
```

MODE_F	PG	---	OFF	2	0	AUTO mode, Feed as M.V.
MODE_M	PG	---	ON	2	0	Manual mode selector
MODE_W	PG	---	OFF	2	0	AUTO mode, W.W. as M.V.
MODE_T	PG	---	OFF	2	0	AUTO mode, Tailings as M.V.
PROLEV	PG	---	ON	2	0	Monitor P1 and select LEV ?
PGSTOP	PG	---	OFF	2	0	Stops ww and tailings pumps
STARTUP	PG	---	ON	2	0	Startup routine
TES	PG	---	OFF	2	0	Rel.Lev.Position, use RATIO
TEST	PG	---	OFF	2	0	Rel.Lev.Position, use DERIV
PID_F	PID	---	ON	---	18	PID - Feed as M.V.
PID_T	PID	---	ON	---	18	PID - Tailings as M.V.
PID_W	PID	---	ON	---	4	PID - Wash Water as M.V.
FSS	SS	---	ON	---	4	Selector to link PID/FC
LEVEQ	SS	---	ON	---	152	Select Level equation
TSS	SS	---	ON	---	4	Selector to link PID/TC
WSS	SS	---	ON	---	4	Selector to link PID/WC

```
!-----------------------------------------------------------------------------------------
!                       Database Blocks List
! Nodename: FIXCOM1                  Date: 09-30-1994

!-----------------------------------------------------------------------------------------

Block Type :: AI
Tag Name   :: AFT

 NEXT BLK        :: GHU
 DESCRIPTION     :: Air Flowmeter
 INITIAL SCAN    :: ON
 SCAN TIME       :: 2
 SMOOTHING       :: 5
 I/O DEVICE      :: OP2
 H/W OPTIONS     ::
 I/O ADDRESS     :: B2:9
 SIGNAL CONDITION:: LIN
 LOW EGU LIMIT   :: 0
 HIGH EGU LIMIT  ::  5
 EGU TAG         :: L/m
 INITIAL A/M STAT:: AUTO
 ALARM ENABLE    :: DISABLE
 ALARM AREA(S)   :: ALL
 LO LO ALARM LIMI:: 0
 LO ALARM LIMIT  :: 0
 HI ALARM LIMIT  :: 10
 HI HI ALARM LIMI:: 10
 ROC ALARM LIMIT :: 0
 DEAD BAND       :: 0
 ALARM PRIORITY  :: L
 SECURITY AREA 1 :: NONE
 SECURITY AREA 2 :: NONE
 SECURITY AREA 3 :: NONE

Block Type :: AI
Tag Name   :: P3

 NEXT BLK        :: EVA_P3
 DESCR :: Bottom Press 0 -> 400 cm H2O
 INITIAL SCAN    :: ON
 SCAN TIME       :: 2
 SMOOTHING       :: 7
 I/O DEVICE      :: OP2
 H/W OPTIONS     ::
 I/O ADDRESS     :: B2:2
 SIGNAL CONDITION:: LIN
 LOW EGU LIMIT   :: 0.00
 HIGH EGU LIMIT  :: 450.00
 EGU TAG         :: cm

Block Type :: DT
Tag Name   :: DT_GHU

 NEXT BLOCK      :: RATIO
 LOW EGU LIMIT   :: 0.00
 HIGH EGU LIMIT  :: 40.00
 EGU TAG         ::
 DEAD TIME       :: 40
 SECURITY AREA 1 :: NONE
 SECURITY AREA 2 :: NONE
 SECURITY AREA 3 :: NONE

Block Type :: DT
Tag Name   :: DT_LEV1

 NEXT BLOCK      ::
 LOW EGU LIMIT   :: 0.00
 HIGH EGU LIMIT  :: 200.00
 EGU TAG         ::
 DEAD TIME       :: 20
 SECURITY AREA 1 :: NONE
 SECURITY AREA 2 :: NONE
 SECURITY AREA 3 :: NONE

Block Type :: DT
Tag Name   :: DT_DEN

 NEXT BLOCK      :: DERIV
 LOW EGU LIMIT   :: 0.00
 HIGH EGU LIMIT  :: 100.00
 EGU TAG         ::
 DEAD TIME       :: 20
 SECURITY AREA 1 :: NONE
 SECURITY AREA 2 :: NONE
 SECURITY AREA 3 :: NONE

Block Type :: SS
Tag Name   :: LEVEQ

 NEXT BLOCK      :: FAN_LEV
 INPUT 2         :: LEV1.F_CV
 INPUT 3         ::
 INPUT 4         ::
 INPUT 5         ::
```

```
INITIAL A/M STAT:: AUTO
ALARM ENABLE    :: DISABLE
ALARM AREA(S)   :: ALL
LO LO ALARM LIMI:: 0.00
LO ALARM LIMIT  :: 0.00
HI ALARM LIMIT  :: 450.00
HI HI ALARM LIMI:: 450.00
ROC ALARM LIMIT :: 0.00
DEAD BAND       :: 0.01
ALARM PRIORITY  :: L
SECURITY AREA 1 :: NONE
SECURITY AREA 2 :: NONE
SECURITY AREA 3 :: NONE
```

Block Type :: AI
Tag Name :: P2

```
NEXT BLK        :: LEV2
DESCRI::Middle Pressure 0->200 cm H2O
INITIAL SCAN    :: ON
SCAN TIME       :: 2
SMOOTHING       :: 7
I/O DEVICE      :: OP2
H/W OPTIONS     ::
I/O ADDRESS     :: B2:1
SIGNAL CONDITION:: LIN
LOW EGU LIMIT   :: 0.00
HIGH EGU LIMIT  :: 160.00
EGU TAG         :: cm
INITIAL A/M STAT:: AUTO
ALARM ENABLE    :: DISABLE
ALARM AREA(S)   :: ALL
LO LO ALARM LIMI:: 0.00
LO ALARM LIMIT  :: 0.00
HI ALARM LIMIT  :: 160.00
HI HI ALARM LIMI:: 160.00
ROC ALARM LIMIT :: 0.00
DEAD BAND       :: 0.01
ALARM PRIORITY  :: L
SECURITY AREA 1 :: NONE
SECURITY AREA 2 :: NONE
SECURITY AREA 3 :: NONE
```

```
INPUT 6         ::
LOW EGU LIMIT   :: 0.00
HIGH EGU LIMIT  :: 180.00
EGU TAG         ::
SELECTION MODE  :: INPUT1
ALARM AREA(S)   :: ALL
SECURITY AREA 1 :: NONE
SECURITY AREA 2 :: NONE
SECURITY AREA 3 :: NONE
```

Block Type :: SS
Tag Name :: FSS

```
NEXT BLOCK      :: FC
INPUT 2         :: FC.F_CV
INPUT 3         ::
INPUT 4         ::
INPUT 5         ::
INPUT 6         ::
LOW EGU LIMIT   :: 4.00
HIGH EGU LIMIT  :: 18.00
EGU TAG         :: mA
SELECTION MODE  :: INPUT2
ALARM AREA(S)   :: ALL
SECURITY AREA 1 :: NONE
SECURITY AREA 2 :: NONE
SECURITY AREA 3 :: NONE
```

Block Type :: SS
Tag Name :: WSS

```
NEXT BLOCK      :: WC
INPUT 2         :: WC.F_CV
INPUT 3         ::
INPUT 4         ::
INPUT 5         ::
INPUT 6         ::
LOW EGU LIMIT   :: 4.00
HIGH EGU LIMIT  :: 18.00
EGU TAG         :: mA
SELECTION MODE  :: INPUT2
ALARM AREA(S)   :: ALL
SECURITY AREA 1 :: NONE
SECURITY AREA 2 :: NONE
SECURITY AREA 3 :: NONE
```

Block Type :: AI
Tag Name :: P1

```
NEXT BLK       :: EVA_P1
DESCRIPT::Top pressure 0 -> 100 cm H2O
INITIAL SCAN   :: ON
SCAN TIME      :: 2
SMOOTHING      :: 7
I/O DEVICE     :: OP2
H/W OPTIONS    ::
I/O ADDRESS    :: B2:0
SIGNAL CONDITION:: LIN
LOW EGU LIMIT  :: 0.00
HIGH EGU LIMIT :: 120.00
EGU TAG        :: cm
INITIAL A/M STAT:: AUTO
ALARM ENABLE   :: DISABLE
ALARM AREA(S)  :: ALL
LO LO ALARM LIMI:: 0.00
LO ALARM LIMIT :: 0.00
HI ALARM LIMIT :: 120.00
HI HI ALARM LIMI:: 120.00
ROC ALARM LIMIT :: 0.00
DEAD BAND      :: 0.01
ALARM PRIORITY :: L
SECURITY AREA 1 :: NONE
SECURITY AREA 2 :: NONE
SECURITY AREA 3 :: NONE
```

Block Type :: AI
Tag Name :: WFT

```
NEXT BLK       ::
DESCRIPT::W.W.Flowrate 0->1.00 cm/sec
INITIAL SCAN   :: ON
SCAN TIME      :: 2
SMOOTHING      :: 10
I/O DEVICE     :: OP2
H/W OPTIONS    ::
I/O ADDRESS    :: B2:4
SIGNAL CONDITION:: LIN
LOW EGU LIMIT  :: 0.001
HIGH EGU LIMIT :: 10.420
EGU TAG        ::
INITIAL A/M STAT:: AUTO
ALARM ENABLE   :: DISABLE
ALARM AREA(S)  :: ALL
LO LO ALARM LIMI:: 0.001
LO ALARM LIMIT :: 0.001
HI ALARM LIMIT :: 10.420
```

Block Type :: SS
Tag Name :: TSS

```
NEXT BLOCK     :: TC
INPUT 2        :: TC.F_CV
INPUT 3        ::
INPUT 4        ::
INPUT 5        ::
INPUT 6        ::
LOW EGU LIMIT  :: 4.00
HIGH EGU LIMIT :: 18.00
EGU TAG        :: mA
SELECTION MODE :: INPUT2
ALARM AREA(S)  :: ALL
SECURITY AREA 1 :: NONE
SECURITY AREA 2 :: NONE
SECURITY AREA 3 :: NONE
```

Block Type :: CA
Tag Name :: LEV1

```
NEXT BLOCK     :: DT_LEV1
DESC :: Calculated level(1)  20 ->180  cm
INPUT B        :: P3.F_CV
INPUT C        :: 315.7
INPUT D        :: 0.34
INPUT E        ::
INPUT F        ::
INPUT G        ::
INPUT H        ::
OUTPUT CALCULATI:: ((C-B)/D)
LOW EGU LIMIT  :: 0.00
HIGH EGU LIMIT :: 180.00
EGU TAG        ::
ALARM ENABLE   :: DISABLE
ALARM AREA(S)  :: ALL
SECURITY AREA 1 :: NONE
SECURITY AREA 2 :: NONE
SECURITY AREA 3 :: NONE
```

Block Type :: CA
Tag Name :: LEV2

```
NEXT BLOCK     :: DEN
DESCRIPTION    :: Calculated level (LEV2)
INPUT B        :: P3.F_CV
INPUT C        :: 154.50
INPUT D        :: 410.40
INPUT E        :: 0.375
INPUT F        :: 255.90
```

```
HI HI ALARM LIMI:: 10.420
ROC ALARM LIMIT :: 0.000
DEAD BAND       :: 0.000
ALARM PRIORITY  :: L
SECURITY AREA 1 :: NONE
SECURITY AREA 2 :: NONE
SECURITY AREA 3 :: NONE
```

Block Type :: AI
Tag Name   :: FFT

```
NEXT BLK        :: GHU2
DESCRIP:: Feed Flowrate 0 ->1.00 cm/sec
INITIAL SCAN    :: ON
SCAN TIME       :: 2
SMOOTHING       :: 5
I/O DEVICE      :: OP2
H/W OPTIONS     ::
I/O ADDRESS     :: B2:5
SIGNAL CONDITION:: LIN
LOW EGU LIMIT   :: 0.00
HIGH EGU LIMIT  :: 25.39
EGU TAG         :: cm/s
INITIAL A/M STAT:: AUTO
ALARM ENABLE    :: DISABLE
ALARM AREA(S)   :: ALL
LO LO ALARM LIMI:: 0.00
LO ALARM LIMIT  :: 0.00
HI ALARM LIMIT  :: 25.39
HI HI ALARM LIMI:: 25.39
ROC ALARM LIMIT :: 0.00
DEAD BAND       :: 0.00
ALARM PRIORITY  :: L
SECURITY AREA 1 :: NONE
SECURITY AREA 2 :: NONE
SECURITY AREA 3 :: NONE
```

Block Type :: AI
Tag Name   :: SAI_LST

```
NEXT BLK        :: FAN_LSP
DESCRIPT::Simul.analog input to set level
INITIAL SCAN    :: ON
SCAN TIME       :: 2
SMOOTHING       :: 5
I/O DEVICE      :: SIM
H/W OPTIONS     ::
I/O ADDRESS     :: 2
```

```
INPUT G         ::
INPUT H         ::
OUT. CALC::(((B*C)-(A*D))/((B-A)-(E*F)))
LOW EGU LIMIT   :: 0.00
HIGH EGU LIMIT  :: 180.00
EGU TAG         ::
ALARM ENABLE    :: DISABLE
ALARM AREA(S)   :: ALL
SECURITY AREA 1 :: NONE
SECURITY AREA 2 :: NONE
SECURITY AREA 3 :: NONE
```

Block Type :: CA
Tag Name   :: LEV3

```
NEXT BLOCK      :: LEVEQ
DESCRIPTION :: Froth depth 20->180 cm
INPUT B         :: P1.F_CV
INPUT C         :: P2.F_CV
INPUT D         :: 45.00
INPUT E         :: 109.50
INPUT F         :: 255.90
INPUT G         :: 154.50
INPUT H         ::
OUT:: (((F*C)-((A-C)*G))/(((F*B)/D)-(A-C)))
LOW EGU LIMIT   :: 0.00
HIGH EGU LIMIT  :: 400.00
EGU TAG         ::
ALARM ENABLE    :: DISABLE
ALARM AREA(S)   :: ALL
SECURITY AREA 1 :: NONE
SECURITY AREA 2 :: NONE
SECURITY AREA 3 :: NONE
```

Block Type :: CA
Tag Name   :: GHU

```
NEXT BLOCK      :: DT_GHU
DESCRIPTION     :: Gas holdup 0 -> 40
INPUT B         :: 1.00
INPUT C         :: P3.F_CV
INPUT D         :: 100.00
INPUT E         :: 255.90
INPUT F         :: P2.F_CV
INPUT G         ::
INPUT H         ::
OUTPUT CALCULATI:: (D*(B-((C-F)/E)))
LOW EGU LIMIT   :: 0.00
HIGH EGU LIMIT  :: 40.00
EGU TAG         ::
```

```
SIGNAL CONDITION::
LOW EGU LIMIT  :: 20
HIGH EGU LIMIT :: 180
EGU TAG        :: cm
INITIAL A/M STAT:: MANL
ALARM ENABLE   :: DISABLE
ALARM AREA(S)  :: ALL
LO LO ALARM LIMI:: 20
LO ALARM LIMIT :: 20
HI ALARM LIMIT :: 180
HI HI ALARM LIMI:: 180
ROC ALARM LIMIT :: 0
DEAD BAND      :: 0
ALARM PRIORITY :: L
SECURITY AREA 1 :: NONE
SECURITY AREA 2 :: NONE
SECURITY AREA 3 :: NONE
```

Block Type :: AI
Tag Name :: SAI_T

```
NEXT BLK       :: PID_T
DESC::Simulated input, Underflow chain
INITIAL SCAN   :: ON
SCAN TIME      :: 2
SMOOTHING      :: 7
I/O DEVICE     :: SIM
H/W OPTIONS    ::
I/O ADDRESS    :: 1
SIGNAL CONDITION::
LOW EGU LIMIT  :: 0.00
HIGH EGU LIMIT :: 200.00
EGU TAG        ::
INITIAL A/M STAT:: AUTO
ALARM ENABLE   :: DISABLE
ALARM AREA(S)  :: ALL
LO LO ALARM LIMI:: 0.00
LO ALARM LIMIT :: 0.00
HI ALARM LIMIT :: 200.00
HI HI ALARM LIMI:: 200.00
ROC ALARM LIMIT :: 0.00
DEAD BAND      :: 0.50
ALARM PRIORITY :: L
SECURITY AREA 1 :: NONE
SECURITY AREA 2 :: NONE
SECURITY AREA 3 :: NONE
```

```
ALARM ENABLE   :: DISABLE
ALARM AREA(S)  :: ALL
SECURITY AREA 1 :: NONE
SECURITY AREA 2 :: NONE
SECURITY AREA 3 :: NONE
```

Block Type :: CA
Tag Name :: RATIO

```
NEXT BLOCK     ::
DESCRIPTION::Ratio [Lev/ghu] -100->100
INPUT B        :: DT_LEV1.F_CV
INPUT C        :: GHU.F_CV
INPUT D        :: LEV1.F_CV
INPUT E        ::
INPUT F        ::
INPUT G        ::
INPUT H        ::
OUTPUT CALCULATI:: ((D-B)/(C-A))
LOW EGU LIMIT  :: -100.00
HIGH EGU LIMIT :: 100.00
EGU TAG        ::
ALARM ENABLE   :: DISABLE
ALARM AREA(S)  :: ALL
SECURITY AREA 1 :: NONE
SECURITY AREA 2 :: NONE
SECURITY AREA 3 :: NONE
```

Block Type :: CA
Tag Name :: DEN

```
NEXT BLOCK     :: DT_DEN
DESCRIPTION :: rc - density at P2
INPUT B        :: P3.F_CV
INPUT C        :: P2.F_CV
INPUT D        :: 410.8
INPUT E        :: 154.5
INPUT F        ::
INPUT G        ::
INPUT H        ::
OUTPUT CALC:: (((B-C)/(D-E))-(C/E))
LOW EGU LIMIT  :: 0.00
HIGH EGU LIMIT :: 100.00
EGU TAG        ::
ALARM ENABLE   :: DISABLE
ALARM AREA(S)  :: ALL
SECURITY AREA 1 :: NONE
SECURITY AREA 2 :: NONE
SECURITY AREA 3 :: NONE
```

Block Type :: AI
Tag Name :: SAI_W

```
NEXT BLK        :: PID_W
DESCRIPTION :: Simulated input, ww chain
INITIAL SCAN    :: ON
SCAN TIME       :: 2
SMOOTHING       :: 7
I/O DEVICE      :: SIM
H/W OPTIONS     ::
I/O ADDRESS     :: 0
SIGNAL CONDITION::
LOW EGU LIMIT   :: 0.00
HIGH EGU LIMIT  :: 200.00
EGU TAG         ::
INITIAL A/M STAT:: AUTO
ALARM ENABLE    :: DISABLE
ALARM AREA(S)   :: ALL
LO LO ALARM LIMI:: 0.00
LO ALARM LIMIT  :: 0.00
HI ALARM LIMIT  :: 200.00
HI HI ALARM LIMI:: 200.00
ROC ALARM LIMIT :: 0.00
DEAD BAND       :: 1.00
ALARM PRIORITY  :: L
SECURITY AREA 1 :: NONE
SECURITY AREA 2 :: NONE
SECURITY AREA 3 :: NONE
```

Block Type :: AO
Tag Name :: FC

```
NEXT BLOCK      ::
DESCRIPTION     :: Feed Controller
I/O DEVICE      :: OP2
H/W OPTIONS     ::
I/O ADDRESS     :: B2:11
SIGNAL CONDITION:: LIN
LOW EGU LIMIT   :: 4.00
HIGH EGU LIMIT  :: 20.00
EGU TAG         ::
COLD START VALUE:: 4.00
OUTPUT REVERSE  :: NO
LOW OPERATOR LIM:: 4.00
HIGH OPERATOR LI:: 20.00
RATE LIMIT      :: 0.00
ALARM ENABLE    :: DISABLE
ALARM AREA(S)   :: ALL
SECURITY AREA 1 :: NONE
SECURITY AREA 2 :: NONE
SECURITY AREA 3 :: NONE
```

Block Type :: CA
Tag Name :: DERIV

```
NEXT BLOCK      ::
DESCRIPTION::Deriv [lev/den]  -200->200
INPUT B         :: DT_LEV1.F_CV
INPUT C         :: DEN.F_CV
INPUT D         :: LEV1.F_CV
INPUT E         ::
INPUT F         ::
INPUT G         ::
INPUT H         ::
OUTPUT CALCULATI:: ((D-B)/(C-A))
LCW EGU LIMIT   :: -200.00
HIGH EGU LIMIT  :: 200.00
EGU TAG         ::
ALARM ENABLE    :: DISABLE
ALARM AREA(S)   :: ALL
SECURITY AREA 1 :: NONE
SECURITY AREA 2 :: NONE
SECURITY AREA 3 :: NONE
```

Block Type :: CA
Tag Name :: GHU2

```
NEXT BLOCK      ::
DESCRIPTION::Gasholdup h2--h1  0->100
INPUT B         :: P1.F_CV
INPUT C         :: P2.F_CV
INPUT D         :: 109.2
INPUT E         :: 100
INPUT F         :: 1
INPUT G         ::
INPUT H         ::
OUTPUT CALCULATI:: (E*(F-((C-B)/D)))
LOW EGU LIMIT   :: 0.00
HIGH EGU LIMIT  :: 400.00
EGU TAG         ::
ALARM ENABLE    :: DISABLE
ALARM AREA(S)   :: ALL
SECURITY AREA 1 :: NONE
SECURITY AREA 2 :: NONE
SECURITY AREA 3 :: NONE
```

Block Type :: AO
Tag Name :: TC

```
NEXT BLOCK     ::
DESCRIPTION :: Tailings pump 4 ->20 mA
I/O DEVICE     :: OP2
H/W OPTIONS    ::
I/O ADDRESS    :: B2:12
SIGNAL CONDITION:: LIN
LOW EGU LIMIT   :: 4.00
HIGH EGU LIMIT  :: 20.00
EGU TAG        ::
COLD START VALUE:: 4.00
OUTPUT REVERSE  :: NO
LOW OPERATOR LIM:: 4.00
HIGH OPERATOR LI:: 20.00
RATE LIMIT      :: 0.00
ALARM ENABLE    :: DISABLE
ALARM AREA(S)   :: ALL
SECURITY AREA 1 :: NONE
SECURITY AREA 2 :: NONE
SECURITY AREA 3 :: NONE
```

Block Type :: AO
Tag Name :: WC

```
NEXT BLOCK     ::
DESCRIPTION    :: Washwater controller
I/O DEVICE     :: OP2
H/W OPTIONS    ::
I/O ADDRESS    :: B2:10
SIGNAL CONDITION:: LIN
LOW EGU LIMIT   :: 4.00
HIGH EGU LIMIT  :: 20.00
EGU TAG        ::
COLD START VALUE:: 4.00
OUTPUT REVERSE  :: NO
LOW OPERATOR LIM:: 4.00
HIGH OPERATOR LI:: 20.00
RATE LIMIT      :: 0.00
ALARM ENABLE    :: DISABLE
ALARM AREA(S)   :: ALL
SECURITY AREA 1 :: NONE
SECURITY AREA 2 :: NONE
SECURITY AREA 3 :: NONE
```

Block Type :: FN
Tag Name :: FAN_LEV

```
NEXT BLOCK      :: PID_F
OUTPUT TAG A    :: SAI_W.F_CV
OUTPUT TAG B    :: SAI_T.F_CV
OUTPUT TAG C    ::
OUTPUT TAG D    ::
ALARM AREA(S)   :: NONE
SECURITY AREA 1 :: NONE
SECURITY AREA 2 :: NONE
SECURITY AREA 3 :: NONE
```

Block Type :: FN
Tag Name :: FAN_LSP

```
NEXT BLOCK      ::
OUTPUT TAG A    :: PID_W.F_TV1
OUTPUT TAG B    :: PID_F.F_TV1
OUTPUT TAG C    :: PID_T.F_TV1
OUTPUT TAG D    ::
ALARM AREA(S)   :: NONE
SECURITY AREA 1 :: NONE
SECURITY AREA 2 :: NONE
SECURITY AREA 3 :: NONE
```

Block Type :: EV
Tag Name :: EVA_P3

```
NEXT BLOCK      :: LEV3
TEST CONDITION 1:: VALUE <        30
TRUE CONDITION 1:: run PGSTOP
FALSE CONDITION:: ----
TEST CONDITION 2:: VALUE >        1
TRUE CONDITION 2:: ----
FALSE CONDITION :: ----
SECURITY AREA 1 :: NONE
SECURITY AREA 2 :: NONE
SECURITY AREA 3 :: NONE
```

Block Type :: PG
Tag Name :: PROLEV

```
DESC::Monitor P1 and toggle SS LEVEQ
INITIAL SCAN    :: ON
SCAN TIME       :: 2
PROG.STAT:: IF  P1  > 1.00 GOTO 1
PROGRAM STATEMEN:: GOTO     0
PROG.STAT:: IF LEV1 > 125.00 GOTO 5
PROG.STAT:: SETSEL  LEVEQ  INPUT1
```

Block Type :: AO
Tag Name :: AC

```
NEXT BLOCK      ::
DESCRIPTION     :: Air Controller
I/O DEVICE      :: OP2
H/W OPTIONS     ::
I/O ADDRESS     :: B2:8
SIGNAL CONDITION:: LIN
LOW EGU LIMIT   :: 0.00
HIGH EGU LIMIT  :: 10.00
EGU TAG         :: L/M
COLD START VALUE:: 0.00
OUTPUT REVERSE  :: NO
LOW OPERATOR LIM:: 0.00
HIGH OPERATOR LI:: 10.00
RATE LIMIT      :: 0.00
ALARM ENABLE    :: DISABLE
ALARM AREA(S)   :: ALL
SECURITY AREA 1 :: NONE
```

Block Type :: DO
Tag Name :: ASV (DIGO_1)

```
NEXT BLOCK      ::
DESCRIPTION :: Switch Air solenoid valve
I/O DEVICE      :: OP2
H/W OPTIONS     ::
I/O ADDRESS     :: B1:0
OPEN TAG        :: OPEN
CLOSE TAG       :: CLOSE
COLD START VALUE:: OPEN
INVERT OUTPUT   :: NO
ALARM ENABLE    :: DISABLE
ALARM AREA(S)   :: ALL
SECURITY AREA 1 :: NONE
```

Block Type :: DO
Tag Name :: MOF

```
NEXT BLOCK      ::
DESCRIPTION :: Flag to signal Manualop
I/O DEVICE      :: OP2
H/W OPTIONS     ::
I/O ADDRESS     :: B1:1
OPEN TAG        :: OPEN
COLD START VALUE:: OPEN
INVERT OUTPUT   :: NO
ALARM ENABLE    :: DISABLE
ALARM AREA(S)   :: ALL
SECURITY AREA 1 :: NONE
```

```
PROGRAM STATEMEN:: GOTO    2
PROG.STAT:: SETSEL LEVEQ INPUT2
PROGRAM STATEMEN:: GOTO    2
PROGRAM STATEMEN:: NUL

INITIAL A/M STAT:: AUTO
ALARM ENABLE    :: ENABLE
ALARM AREA(S)   :: ALL
ALARM PRIORITY  :: L
SECURITY AREA 1 :: NONE
SECURITY AREA 2 :: NONE
SECURITY AREA 3 :: NONE
```

Block Type :: PG
Tag Name :: STARTUP

```
DESCRIPTION     ::  Startup procedure
INITIAL SCAN    :: OFF
SCAN TIME       :: 10
PROGRAM STAT:: WAITFOR P2 > 55
PROGRAM STATEMEN:: SETOUT AC  3
PROGRAM STATEMEN::SETOUT TC 6.5
PROGRAM STAT:: SETOUT  WC  7.5
PROGRAM STAT:: SETOUT   FC    9.0
PROGRAM STATEMEN:: DELAY  60
PROGRAM STAT:: STOP  MODE_M
PROGRAM STATEMEN:: RUN MODE_T
PROGRAM STATEMEN:: NUL
PROGRAM STATEMEN:: NUL

INITIAL A/M STAT:: AUTO
ALARM ENABLE    :: ENABLE
ALARM AREA(S)   :: ALL
ALARM PRIORITY  :: L
SECURITY AREA 1 :: NONE
SECURITY AREA 2 :: NONE
SECURITY AREA 3 :: NONE
```

Block Type :: PG
Tag Name :: TES

```
DESC::Monitor RATIO and toggle DIGO_1
INITIAL SCAN    :: OFF
SCAN TIME       :: 2
PROGRAM STATEMEN:: DELAY    120
PROG.STAT:: IF RATIO > 17.00 GOTO 5
PROG.STAT:: IF RATIO <  0.00 GOTO 5
PROGRAM STAT:: CLOSE  DIGO_1
PROGRAM STATEMEN:: END
PROGRAM STAT:: OPEN   DIGO_1
```

```
Block Type :: DO
Tag Name   :: AOF

 NEXT BLOCK      ::
 DESCRIPTION :: Flag to signal autom.oper.
 I/O DEVICE      :: OP2
 H/W OPTIONS     ::
 I/O ADDRESS     :: B1:2
 OPEN TAG        :: OPEN
 CLOSE TAG       :: CLOSE
 COLD START VALUE:: OPEN
 INVERT OUTPUT   :: NO
 ALARM ENABLE    :: DISABLE
 ALARM AREA(S)   :: ALL
 SECURITY AREA 1 :: NONE
 ALARM PRIORITY  :: L
 SECURITY AREA 1 :: NONE

Block Type :: DO
Tag Name   :: TIV

 NEXT BLOCK      ::
 DESCRIPTION::switch  Top isol. Valve
 I/O DEVICE      :: OP2
 H/W OPTIONS     ::
 I/O ADDRESS     :: B1:3
 OPEN TAG        :: OPEN
 CLOSE TAG       :: CLOSE
 COLD START VALUE:: OPEN
 INVERT OUTPUT   :: NO
 ALARM ENABLE    :: DISABLE
 ALARM AREA(S)   :: ALL
 SECURITY AREA 1 :: NONE

Block Type :: DO
Tag Name   :: BIV

 NEXT BLOCK      ::
 DESCRIPTION::Switch Bottom Isol.Valve
 I/O DEVICE      :: OP2
 H/W OPTIONS     ::
 I/O ADDRESS     :: B1:4
 OPEN TAG        :: OPEN
 CLOSE TAG       :: CLOSE
 COLD START VALUE:: OPEN
 INVERT OUTPUT   :: NO
 ALARM ENABLE    :: DISABLE
 ALARM AREA(S)   :: ALL
 SECURITY AREA 1 :: NONE
```

```
 PROGRAM STATEMEN:: END
 PROGRAM STATEMEN:: NUL

 INITIAL A/M STAT:: AUTO
 ALARM ENABLE    :: ENABLE
 ALARM AREA(S)   :: ALL
 ALARM PRIORITY  :: L
 SECURITY AREA 1 :: NONE
 SECURITY AREA 2 :: NONE

Block Type :: PG
Tag Name   :: TEST

 DESC::Monitor DERIV and toggle DIGO_1
 INITIAL SCAN    :: OFF
 SCAN TIME       :: 2
 PROG.STAT::IF DERIV < 0.00 GOTO 3
 PROG.STATEMEN:: OPEN     DIGO_1
 PROGRAM STATEMEN:: END
 PROGRAM STAT :: CLOSE    DIGO_1
 PROGRAM STATEMEN:: END
 PROGRAM STATEMEN:: NUL

 INITIAL A/M STAT:: AUTO
 ALARM ENABLE    :: ENABLE
 ALARM AREA(S)   :: ALL
 SECURITY AREA 2 :: NONE
 SECURITY AREA 3 :: NONE

Block Type :: PG
Tag Name   :: MODE_M

 DESCRIPTION     :: Switch to MANUAL
 INITIAL SCAN    :: ON
 SCAN TIME       :: 2
 PROGRAM STAT::SETSEL WSS INPUT2
 PROGRAM STAT::SETSEL FSS INPUT2
 PROGRAM STATEMEN:: SETSEL  TSS I
 PROGRAM STATEMEN:: OPEN    AOF
 PROGRAM STATEMEN:: CLOSE   MOF
 PROGRAM STATEMEN:: GOTO    0
 PROGRAM STATEMEN:: NUL

 INITIAL A/M STAT:: AUTO
 ALARM ENABLE    :: ENABLE
 ALARM AREA(S)   :: ALL
 ALARM PRIORITY  :: L
 SECURITY AREA 1 :: NONE
 SECURITY AREA 2 :: NONE
 SECURITY AREA 3 :: NONE
```

Block Type :: PID
Tag Name :: PID_W

```
NEXT BLOCK      :: WSS
LOW EGU LIMIT   :: 0.00
HIGH EGU LIMIT  :: 180.00
EGU TAG         :: cm
LOW OUTPUT LIMIT:: 4.00
HIGH OUTPUT LIMI:: 18.00
OUTPUT EGU TAG  :: mA
INITIAL A/M STAT:: AUTO
TRANSFER STATUS :: TRACK
FEEDBACK TAG    ::
REVERSE OUTPUT  :: YES
PROPORTIONAL BAN:: 150.00
INTEGRAL TIME   :: 1.50
DERIVATIVE TIME :: 0.05
LOW SETPOINT CLA:: 3.27
HIGH SETPOINT CL:: 168.00
SETPOINT TAG    :: 100.00
DEAD BAND VALUE :: 0.10
DEVIATION VALUE :: 0.00
GAP ACTION      :: 0.00
ALPHA-RATE FACTO:: 0.00
BETA-PBAND FACTO:: 1.00
GAMMA-RESET FACT:: 1.00
ALARM ENABLE    :: DISABLE
ALARM AREA(S)   :: ALL
SECURITY AREA 1 :: NONE
SECURITY AREA 2 :: NONE
SECURITY AREA 3 :: NONE
```

Block Type :: PID
Tag Name :: PID_F

```
NEXT BLOCK      :: FSS
LOW EGU LIMIT   :: 0.00
HIGH EGU LIMIT  :: 180.00
EGU TAG         :: cm
LOW OUTPUT LIMIT:: 4.00
HIGH OUTPUT LIMI:: 18.00
OUTPUT EGU TAG  :: mA
INITIAL A/M STAT:: AUTO
TRANSFER STATUS :: BALANCE
FEEDBACK TAG    ::
REVERSE OUTPUT  :: YES
PROPORTIONAL BAN:: 180.00
INTEGRAL TIME   :: 1.20
DERIVATIVE TIME :: 0.05
LOW SETPOINT CLA:: 3.27
```

Block Type :: PG
Tag Name :: MODE_F

```
DESCRIPT   :: AUTO mode M.V. Feed
INITIAL SCAN   :: OFF
SCAN TIME      :: 2
PROG.STAT::SETSEL   WSS  INPUT2
PROG.STAT::SETSEL   TSS  INPUT2
PROG.STAT::SETSEL   FSS  INPUT1
PROGRAM STATEMEN:: OPEN     MOF
PROGRAM STATEMEN:: CLOSE    AOF
PROGRAM STATEMEN:: GOTO     0
PROGRAM STATEMEN:: NUL

INITIAL A/M STAT:: AUTO
ALARM ENABLE    :: ENABLE
ALARM AREA(S)   :: ALL
ALARM PRIORITY  :: L
SECURITY AREA 1 :: NONE
SECURITY AREA 2 :: NONE
SECURITY AREA 3 :: NONE
```

Block Type :: PG
Tag Name :: MODE_W

```
DESC :: AUTO mode M.V. Wash Water
INITIAL SCAN   :: OFF
SCAN TIME      :: 2
PROG.STAT::SETSEL   FSS  INPUT2
PROG.STAT::SETSEL   TSS  INPUT2
PROG.STAT::SETSEL   WSS  INPUT1
PROGRAM STATEMEN:: OPEN   MOF
PROGRAM STATEMEN:: CLOSE  AOF
PROGRAM STATEMEN:: GOTO     0
PROGRAM STATEMEN:: NUL

INITIAL A/M STAT:: AUTO
ALARM ENABLE    :: ENABLE
ALARM AREA(S)   :: ALL
ALARM PRIORITY  :: L
SECURITY AREA 1 :: NONE
SECURITY AREA 2 :: NONE
SECURITY AREA 3 :: NONE
```

```
HIGH SETPOINT CL:: 168.00
SETPOINT TAG    :: 100.00
DEAD BAND VALUE :: 0.10
DEVIATION VALUE :: 0.00
GAP ACTION      :: 0.00
ALPHA-RATE FACTO:: 0.00
BETA-PBAND FACTO:: 1.00
GAMMA-RESET FACT:: 1.00
ALARM ENABLE    :: DISABLE
ALARM AREA(S)   :: ALL
SECURITY AREA 1 :: NONE
SECURITY AREA 2 :: NONE
SECURITY AREA 3 :: NONE
```

Block Type :: PID
Tag Name :: PID_T

```
NEXT BLOCK      :: TSS
LOW EGU LIMIT   :: 0.00
HIGH EGU LIMIT  :: 180.00
EGU TAG         :: cm
LOW OUTPUT LIMIT:: 4.00
HIGH OUTPUT LIMI:: 18.00
OUTPUT EGU TAG  :: mA
INITIAL A/M STAT:: AUTO
TRANSFER STATUS :: TRACK
FEEDBACK TAG    ::
REVERSE OUTPUT  :: NO
PROPORTIONAL BAN:: 150.00
INTEGRAL TIME   :: 1.50
DERIVATIVE TIME :: 0.05
LOW SETPOINT CLA:: 3.27
HIGH SETPOINT CL:: 168.00
SETPOINT TAG    :: 100.00
DEAD BAND VALUE :: 0.10
DEVIATION VALUE :: 0.00
GAP ACTION      :: 0.00
ALPHA-RATE FACTO:: 0.00
BETA-PBAND FACTO:: 1.00
GAMMA-RESET FACT:: 1.00
ALARM ENABLE    :: DISABLE
ALARM AREA(S)   :: ALL
SECURITY AREA 1 :: NONE
SECURITY AREA 2 :: NONE
SECURITY AREA 3 :: NONE
```

Block Type :: PG
Tag Name :: MODE_T

```
DESCRIP::AUTO mode M.V. Underflow
INITIAL SCAN    :: OFF
SCAN TIME       :: 2
PROG.STAT::SETSEL   WSS  INPUT2
PROG.STAT::SETSEL   FSS INPUT2
PROG.STAT::SETSEL   TSS  INPUT1
PROGRAM STATEMEN:: OPEN  MOF
PROGRAM STATEMEN:: CLOSE  AOF
PROGRAM STATEMEN:: GOTO     0
PROGRAM STATEMEN:: NUL

INITIAL A/M STAT:: AUTO
ALARM ENABLE    :: ENABLE
ALARM AREA(S)   :: ALL
ALARM PRIORITY  :: L
SECURITY AREA 1 :: NONE
SECURITY AREA 2 :: NONE
SECURITY AREA 3 :: NONE
```

Block Type :: PG
Tag Name :: PGSTOP

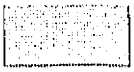
```
DESCRIPT::Stop pumps according to P3
INITIAL SCAN    :: OFF
SCAN TIME       :: 2
PROGRAM STATEMEN:: SETOUT  TC  4
PROGRAM STATEMEN::SETOUT WC  4
PROGRAM STATEMEN:: END
PROGRAM STATEMEN:: NUL
PROGRAM STATEMEN:: NUL
PROGRAM STATEMEN:: NUL
PROGRAM STATEMEN:: NUL

INITIAL A/M STAT:: AUTO
ALARM ENABLE    :: ENABLE
ALARM AREA(S)   :: ALL
ALARM PRIORITY  :: L
SECURITY AREA 1 :: NONE
SECURITY AREA 2 :: NONE

!---------------------------- End of Block List -----
```

APPENDIX 2

DESCRIPTION OF ELEMENTS IN THE SCREEN CONTROL LAYOUT

The schematic representation of the process in the control terminal, includes the following elements:

1. Windows linked to output blocks

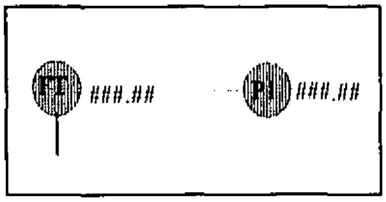


Are represented by yellow rectangles, placed below the corresponding instrument or equipment, they are linked with: 3 pumps, which control the washwater, feed and underflow streams, and a control valve which controls the air flowrate.

Through this elements we can set the values of this variables, in the range of 4 to 20 mA, for the pumps, and from 0 to 5 volts, for the air controller, which is equivalent to l/min reduced to standard conditions.

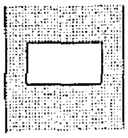
When a given pump controller window, is linked to the output of a PID block, in automatic mode, it is not possible to write values in this window.

2. Input points



The elements linked to input blocks, are used to read values from the instruments, this are represented by small grey circles, coded as FT (flow transmitters) for the flowmeters, and as P1, P2 and P3 for the pressure transducers. There is no special windows for these values, they appear directly beside the instrument representation in the screen. The air flowrate unit is l/min, all other streams are in cm/sec. The readings from the pressure gages are in cm of H_2O.

3. Calculated values

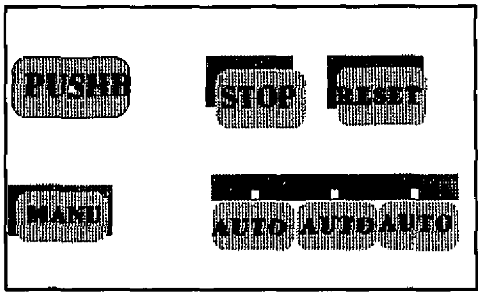


Two white windows labelled as **Level** and **Gas holdup** are linked to the calculation blocks LEV3 and GHU of the database, which display the calculated level (with 3 Pressure transducers), and the gas holdup of the column section between P2 and P3.

4. Level set point

The window created to input the level set point, is represented by a white rectangle with a blue frame.
The value written here is send in parallel to the three PID's configured in the database.

5. Pushbuttons



These are grey rectangles as those represented in this picture, which perform the following tasks:

5.1 FLOWRATE, PRESSURE and LEVTEST

When actuated by clicking with the mouse, they will display data trend diagrams which include curves of flowrates, calculated level, gas holdup, pressure, and so on. The LEVTEST gives information on relative true interface position as compared with P2 position.

5.2 VALVES

Displays a picture created to actuate the isolating valves and the main air line, opening and closing solenoid valves, the elements are linked to the digital output blocks: **TIV**, **BIV** and **SV_A**

5.3 HISTOCOLL

Run fix-dmacs task programs: HC (historical collection) and HD (historical display). Using this option we can start collection and display data, according to preset formats.

5.4 STOP and RESET

Execute a program used to stop an experiment or to continue using the last settings.

5.5 LEVEL TEST and RESET

Run short programs to induce a step in the level and read data after a given delay, to recognize if the true level is above or below P2. The reset option, replace the level at the initial position.

5.6 MANUAL, AUTO_F, AUTO_T and AUTO_W

Run programs to set the operation in manual or automatic mode. The automatic options are set to use alternatively the tailings, washwater or feed streams as manipulated variables.