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The consolidation of the Czochralski Growth Control System(CGCS) is a revision of the hardware and software within the contraints of the first generation. The consolidation consists of: a cabinet that is physically more compatible with the Cambridge console; a more modular hardware arrangement that facilitates calibration, servicing, and expansion; increased accuracy and stability of the system variable measurements; and many software enhancements, including increased controller flexibility and improved diameter estimation and control. The hardware and software installation has been completed and crystal growth with complete digital control has been demonstrated.

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AUTONOMOUS CONTROL SYSTEM FOR CZOCHRALSKI GROWTH OF LEC GaAs

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ABSTRACT

The consolidation of the Czochralski Growth Control System (CGCS) is a revision of the hardware and software within the constraints of the first generation. The consolidation consists of: a cabinet that is physically more compatible with the Cambridge console; a more modular hardware arrangement that facilitates calibration, servicing, and expansion; increased accuracy and stability of the system variable measurements; and many software enhancements, including increased controller flexibility and improved diameter estimation and control.

CONSOLIDATION OF THE CZOCHRALSKI GROWTH CONTROL SYSTEM

R. C. White and B. Luger

1. INTRODUCTION

The Czochralski Growth Control System (CGCS) consists of a digital system which, together with a Cambridge Instruments console, controls a Cambridge Instruments 358 high pressure puller. The CGCS was constructed as a research instrument for the development of autonomous digital control of liquid encapsulated growth of single crystal gallium arsenide. When this research reached a point where the CGCS hardware and software could successfully grow high quality crystals, the next task was to consolidate the system so that the technology could be transferred to other potential users.

This consolidation consists of a revision of the CGCS hardware and software within the current framework. Our aim was to maximize the performance and flexibility of the system without proceeding to a new generation of hardware and software. Specific features of the consolidation include:

- A more modular arrangement of the hardware to facilitate calibration and servicing, and to accommodate additional sensors or actuators.

- A cabinet that is physically more compatible with the Cambridge console.
- Improvements in the analog input hardware.
- Software enhancements.

Figure 1 is a photograph of the Cambridge console (left) and the digital console (right), with a crystal grown by the digital system on the digital console shelf. Figure 2 is a view of the digital console, showing from top to bottom: the digital pen recorder, the flexible disk drives, the work shelf with the crystal, the digital microcomputer, and the input-output subsystem. This report gives a brief description of the CGCS and the improvements implemented in its consolidation.

2. DESCRIPTION OF THE CGCS

2.1 HARDWARE

The crystal growth system comprises three main parts shown in Figure 3: the Cambridge Instruments puller and two systems for controlling the puller: the Cambridge Instruments analog console, and ASU's digital console. A switch, set by the digital console, determines whether the analog or digital console controls the puller. The physical division of the system is not exactly as indicated by Figure 3. When the digital console is in control, it does use of some hardware components in the analog console. However, the division as shown is conceptually useful.

The ASU digital console is shown in more detail in Figure 4. The components of this system, which communicate via the Intel Multibus*, can be conceptually grouped as shown by the dashed lines.

The center of operations is the Processor and Memory section. The CPU (central processing unit) is an Intel Single Board Computer, including an 8085 microprocessor, 16 KBytes of read-only memory, 8 KBytes of random access memory, and an arithmetic processor to speed numerical calculations. The Memory Expansion board provides an additional 48 KBytes of random access memory. The Disk Controller manages two Flexible Disk Drives. One drive stores programs that are loaded into the random access memory for execution, while the other stores crystal growth data for off-line analysis following the run.

The Analog Input section accepts analog data from the puller for transfer to the digital processor. The following analog sources are monitored:

- Three thermocouples that measure the three heater-zone temperatures. (The system currently includes only one heater.)

- Three wattmeters connected to the puller heaters. (Only one is currently used.)

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* The following are registered trademarks of Intel Corporation: Multibus, ISIS, iRMX.

- Four tachometers that measure the motor speeds for lift and rotation of the seed and the crucible.
- Two potentiometers that monitor the seed lift and crucible lift positions.
- The crystal weight gauge.
- An analog differentiator that provides the time derivative of the weight gauge signal.
- A gauge that senses gas pressure inside the puller.
- An electrical contact device that indicates contact between the seed and the boric oxide or between the seed and the GaAs melt.
- Eight spare channels that can be used to monitor supplementary devices.

Isolation amplifiers provide preamplification of the analog signals and separate the analog and digital circuitry to eliminate ground loops. The analog signals are passed through a Filter to remove high-frequency components that would otherwise corrupt (alias) the sampled signals. The analog signals are then multiplexed and fed to a 16-bit A/D converter which makes the digitized data available to the CPU via the Multibus.

The Analog and Digital Output section takes signals from the CPU via the Multibus and sends them to the puller or to a

Printer and a Pen Recorder in the Operator Interface section. (As noted above, some of the signals indicated in Figure 1 as going directly to the puller actually go to hardware components currently located in the analog console.) The D/A converter accepts 12-bit digital signals and converts them to analog equivalents. These signals are:

- Three heater SCR control voltages. (The system currently uses only one heater).
- Four voltages to control the speeds of motors for lift and rotation of the seed and crucible.
- Eight signals routed to the Pen Recorder for monitoring important crystal growth signals.

Digital output signals are fed through the I/O Expansion board to the Relay Board. One relay determines whether the digital console or the analog console controls the four motors that lift and rotate the seed and the crucible. If the digital console is in control, the other relays determine whether each motor is stopped, directed clockwise, or directed counterclockwise.

The Operator Interface section provides for communication between the user and the digital console via the CRT Terminal, the Printer, and the 8-channel Pen Recorder. The operator monitors the status of the crystal growth from data automatically written to the CRT screen and commands the system through the keyboard. The line printer periodically records the crystal growth data, and also copies the operator-system dialog from the CRT terminal. This provides a record of events for reference during and after the crystal growth. The Pen Recorder provides continuous graphical output of system variables such as heater temperature and crystal diameter that are important for monitoring the growth and for analysis following the run.

2.2 SOFTWARE

The CGCS computer utilizes Intel's iRMX-80 real-time operating system for control of the crystal puller. However, as it was desirable to have the system operate in a stand-alone mode in order to execute utility functions (e.g., disk formatting and file maintenance), an operating system emulator was designed that allows the use of software written for Intel's development system environment ISIS-II. The resulting CGCS operating system, named RXISIS-II, provides access to a number of programs, including a BASIC interpreter, a full-screen text editor, and programs for displaying and editing disk files. The computer comes up under RXISIS-II, and the growth control software can be invoked as any other program.

Once the growth control program is invoked, control of the puller and data recording is accomplished by using a set of thirty-one commands. These include, for example, a command to set the seed lift speed, or a command to ramp the heater temperature from its current value to another value over a specified time interval. A powerful software feature is the ability to construct sequences of these commands, called macros. One macro can call another macro in one of two ways: (i) unconditionally, as the last statement of the macro; or (ii) conditionally, using an "IF" command that transfers control to another macro upon fulfillment of a defined condition. Thus, a program for crystal growth can be constructed as a series of macros, with the procedure automatically modified according to the progress of the growth. In this way "intelligent" control of the process is realized.

3. ENHANCEMENT OF THE INPUT-OUTPUT SUBSYSTEM

The analog input subsystem serves as an interface between the pertinent Cambridge Instruments console hardware and the ASU digital console. It provides the following five functions:

1) Terminals to physically connect the input signals coming from the Cambridge Instruments console and the output signals going to the Cambridge Instruments console.

2) Electrical Isolation of the input signals in order to prevent induction of hum and to minimize possible interference between the Cambridge console and the digital console.

3) Filtering of the input signals to remove high-frequency components; this filter is required for eliminating signal components with a frequency greater than half the sampling frequency (currently 1 Hz) which could otherwise cause aliasing of the sampled data.

4) Providing well defined signal levels to the analog-to-digital converter to use its full dynamic range. This is done either by attenuation or amplification of the input signal.

5) Test points for monitoring the processed (isolated and filtered) input and output signals.

The processed input signals are then submitted for analog-to-digital conversion and fed via the Multibus to the 8085-based control system.

The first version of the input-output system was designed so that the analog input circuit boards were physically compatible with the Multibus boards. As a result each board held several input signal processors. Although the first design worked reasonably well, the following disadvantages were revealed after some time:

1) A failure of one channel of the subsystem would have required replacing either a circuit board with several channels or the whole subsystem. This would have been practically impossible had a failure occurred during a crystal growth.

2) There was no room for future expansion.

3) The isolation amplifiers showed considerable drift of the offset voltage and gain with respect to time, temperature and supply voltage.

4) Due to the drift periodic checks and, if necessary, adjustments were required before each growth run. This

adjustment was also subject to error which could jeopardize a run.

5) Identical input stages were used for each channel. As there is a wide dynamic range of the input signals provided by the Cambridge Instruments console, the calibration was very delicate and time consuming.

These disadvantages led to the development of the second version of the analog input subsystem.

The subsystem now consists of two card cages, each of which can hold up to 11 independent analog data preprocessing units. The card cages provide the necessary mechanical stability for the inserted preprocessing units, well defined electrical connections to the analog-to-digital converter, and the necessary supply voltages. The design of each analog preprocessing unit is therefore only limited mechanically by the physical space available and electrically by the pinout of the connector and by the requirements of the analog-to-digital converter. This approach permits the required flexibility and also allows for future expansion.

On the software side the relation between the physical input channels and the logical data used by the controller software is determined by a software-based table of variable length. This table links each physical input channel to an input data-array and can be modified easily, even during a growth run. Therefore in case of a failure of one of the input channels, either the questionable input preprocessing unit can be replaced or a spare input channel can be activated. This can be done very quickly and during a growth run.

Currently two types of input preprocessing units are used:

- thermocouple conditioning modules
- isolation amplifier modules

The thermocouple conditioning module amplifies the low-level thermocouple signal. The built-in cold junction compensation ensures accurate process temperature measurements independent of changes of the ambient temperature.

All other signals generated by the Cambridge Instruments console are processed by the isolation amplifier modules. The input stage of each of these modules is customized to fit the wide variety of signals generated by the puller. The coarse gain can be set by jumpers, while the vernier gain adjustment is specific for each module and therefore allows precise and stable calibration. However, there are some general purpose modules available which could replace the customized modules quickly.

Also an improved offset adjustment circuitry greatly reduced the stability problems noticed in the previous version.

4. SOFTWARE IMPROVEMENTS

In the course of developing the CGCS software, nine program versions were produced. We describe here a few of the features added during the consolidation phase of the development.

Diameter evaluation. The solution for the current diameter was improved by using a one-step solution rather than an iterative solution based on past growth rate data. Figure 5 shows the more stable response of the estimated diameter in response to step changes in differential weight. The effect on crystal growth data is illustrated in Figure 6, where the high-frequency noise in the estimated diameter is reduced in the lower plot.

Diameter estimation was further improved by revising the method of storing past values of crystal diameter, which are used to estimate the diameter of the crystal at the boric oxide surface in order to compensate for the buoyancy force. The original method is illustrated in Figure 7a. Each slice of about 1 mm thickness is represented by a diameter value at the top, which is set equal to the value at the bottom of the preceding slice, and a value at the bottom, which is determined by the value at the top and the computed volume grown during that slice. This proceeds naturally from the beginning of growth because the diameter of the seed is known. However, if, for example, the volume of slice k+1 is computed falsely large due to noisy differential weight measurements, the erroneous diameter at the bottom of that slice propagates to the next slice k+2. In Figure 7a, the volume of slice k+2 is equal to that of slice k, but its bottom diameter d(k+2) is small due to the large value of d(k+1). For most crystal growths this method worked adequately; however, during one growth the error propagation introduced significant oscillations. The estimation was made more stable by computing for each slice a single value of diameter determined only by the volume computed for that slice (Figure 7b). To further reduce the effects of noisy measurements, the diameter d(k+1) of slice k+1 is permitted to differ from d(k) by only a limited amount. The diameter at the oxide surface is interpolated from the diameters of the slices.

Melt recession compensation. As the molten GaAs is depleted near the end of the growth, the melt recedes from the crucible wall, effectively negating the assumption of a straight crucible wall used in the diameter estimation algorithm. A macro-programmmable parameter was introduced to compensate partially for this effect,. and the macros controlling the tail growth were modified. The improvement in diameter control is indicated by a series of photographs: two crystals grown consecutively with the same settings on the analog controller (Figure 8), a crystal grown digitally without melt recession compensation (Figure 9), and two crystals grown digitally with adjusted tail growth macros and with compensation for melt recession (Figure 10). The practical value of this improvement is to increase the yield of wafers from the crystal. The crystal remains single throughout the tail, whereas growth by conventional analog control produces a polycrystalline tail section.

PID controller. Several features were added to increase the flexibility of the PID (Proportional-Integral-Derivative) controller algorithm for motor control. Figure 11 is a somewhat simplified diagram of the motor speed control loop. The original Cambridge Instruments motor with its own analog feedback controller is quick but suffers from poor steady-state accuracy. Adding the digital PID controller eliminates steady-state errors at constant speed. However, the transient response is slower due to the delay through the low-pass analog filter, which is required to prevent aliasing errors at the sampling frequency of 1 Hz. The feedforward channel with programmable gain KF was introduced to permit pure analog control (KF=1, L=0) during dipping, where fast response is desired and steady state accuracy is not required, and digital control (KF=0, L>0) during growth, where steady state accuracy is important and quick response is not required. A further improvement is the ability to set the values of the integral channel output XI and the previous error E(n-1) by an operator command or by a command in a growth control macro. For example, transients can be induced when returning to automatic control after a manual control override during maintenance operations, or when changing from pure analog control to digital control at the beginning of growth. Setting XI and E(n-1) to zero prior to restoring digital feedback control eliminates these transients.

5. CONCLUSIONS

The consolidation of the CGCS hardware and software has improved the system in several respects.

The new version of the software is superior in terms of performance and flexibility. The algorithms provide more accurate calculation of the crystal growth, and the introduction of new controller parameters allows one to tailor the controller to the different stages of the process. In combination with the macro-command language, these enhancements result in very flexible and intelligent control of the growth process.

The introduction of a modular hardware concept allows for future expansions and greatly enhances the system's reliability and serviceability. The hardware modifications also have improved the accuracy and stability of the system variable measurements.

In summary, the consolidation has significantly improved the CGCS making it a powerful and flexible tool for crystal growth with good reproducibility of the process parameters.

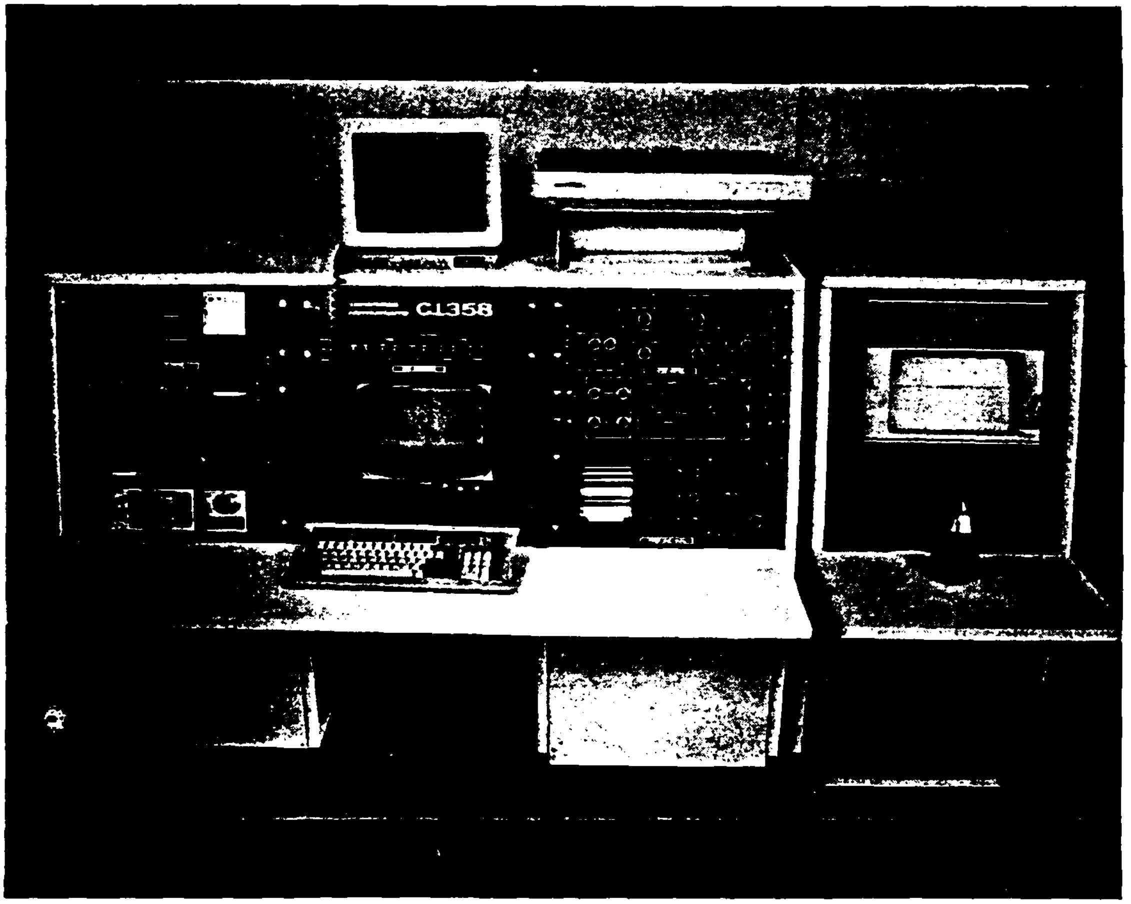


Figure 1. The Cambridge Instruments console and the ASU digital console.

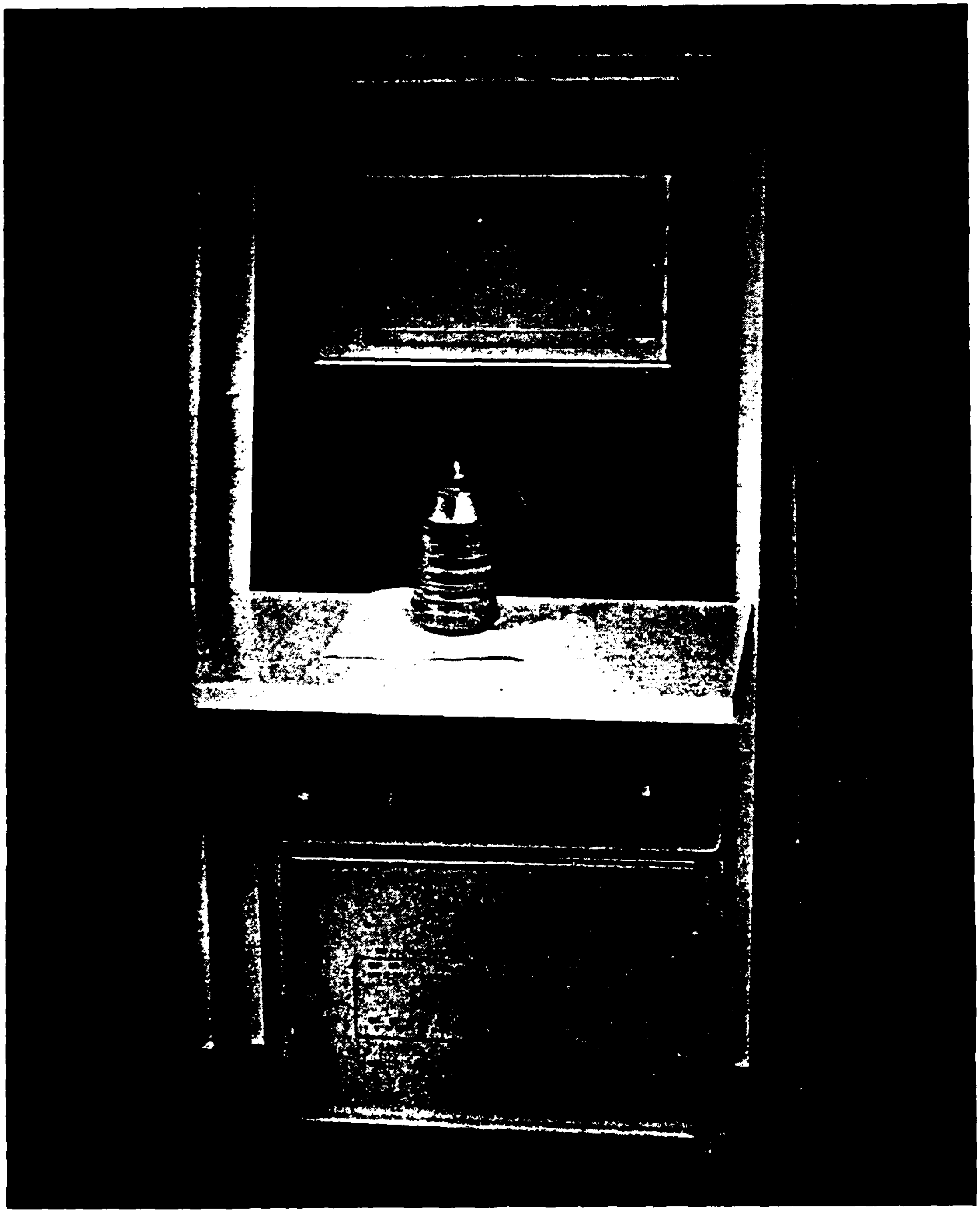


Figure 2. The ASU digital console.

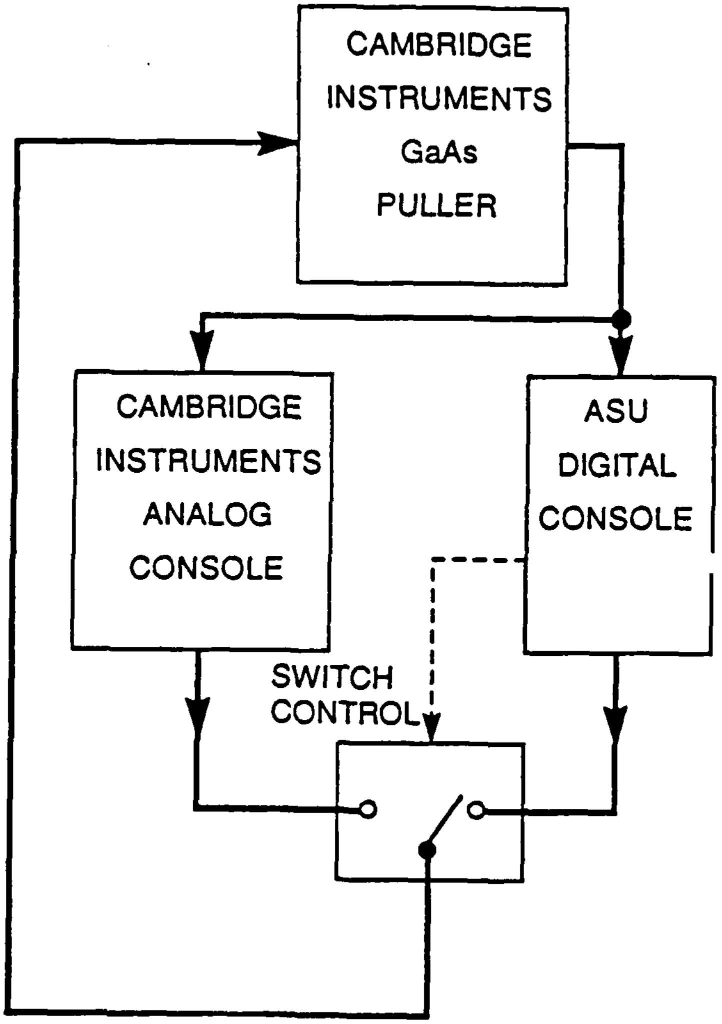


Figure 3. The puller and its connections to the two consoles.

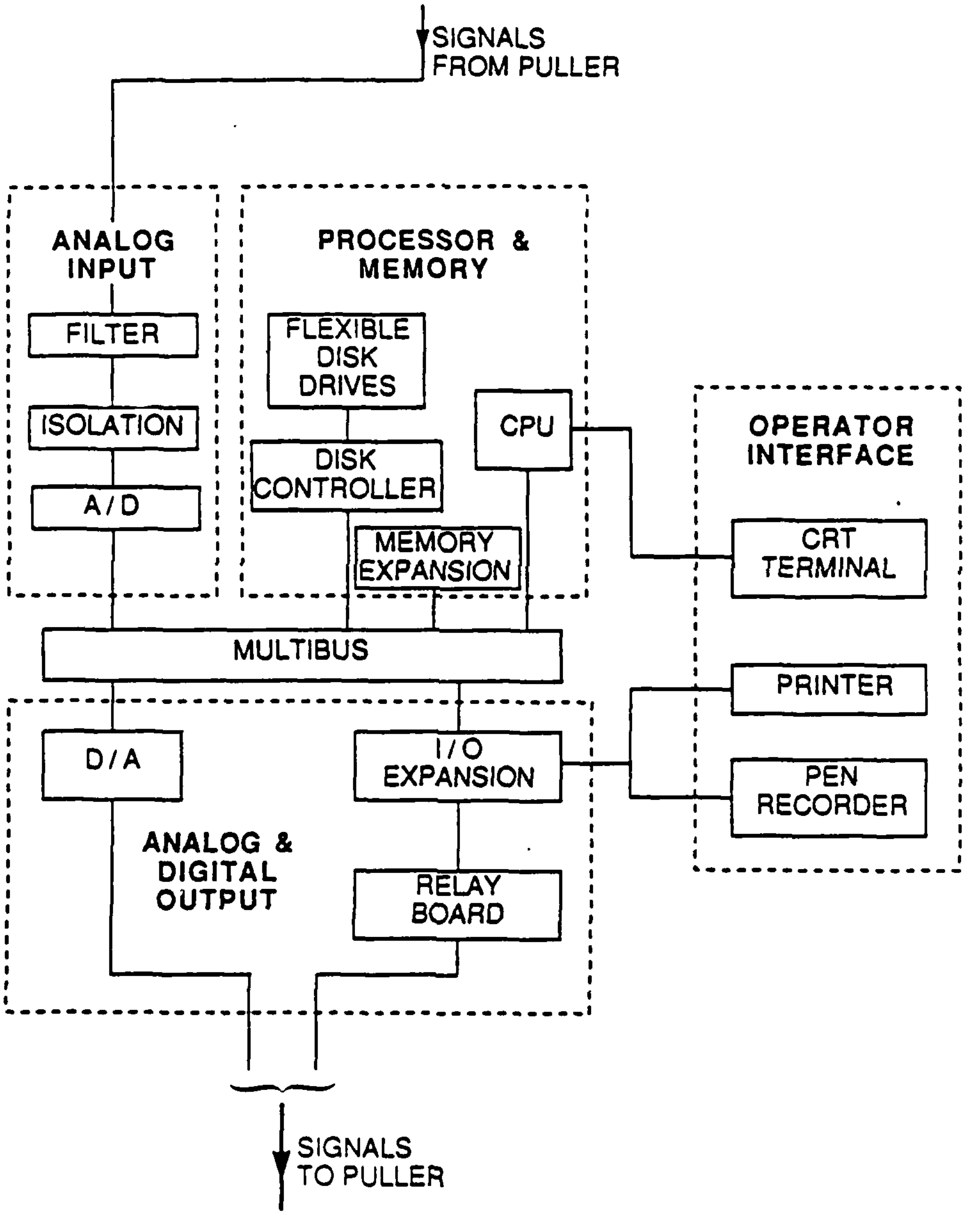


Figure 4. A block diagram of the ASU digital console.

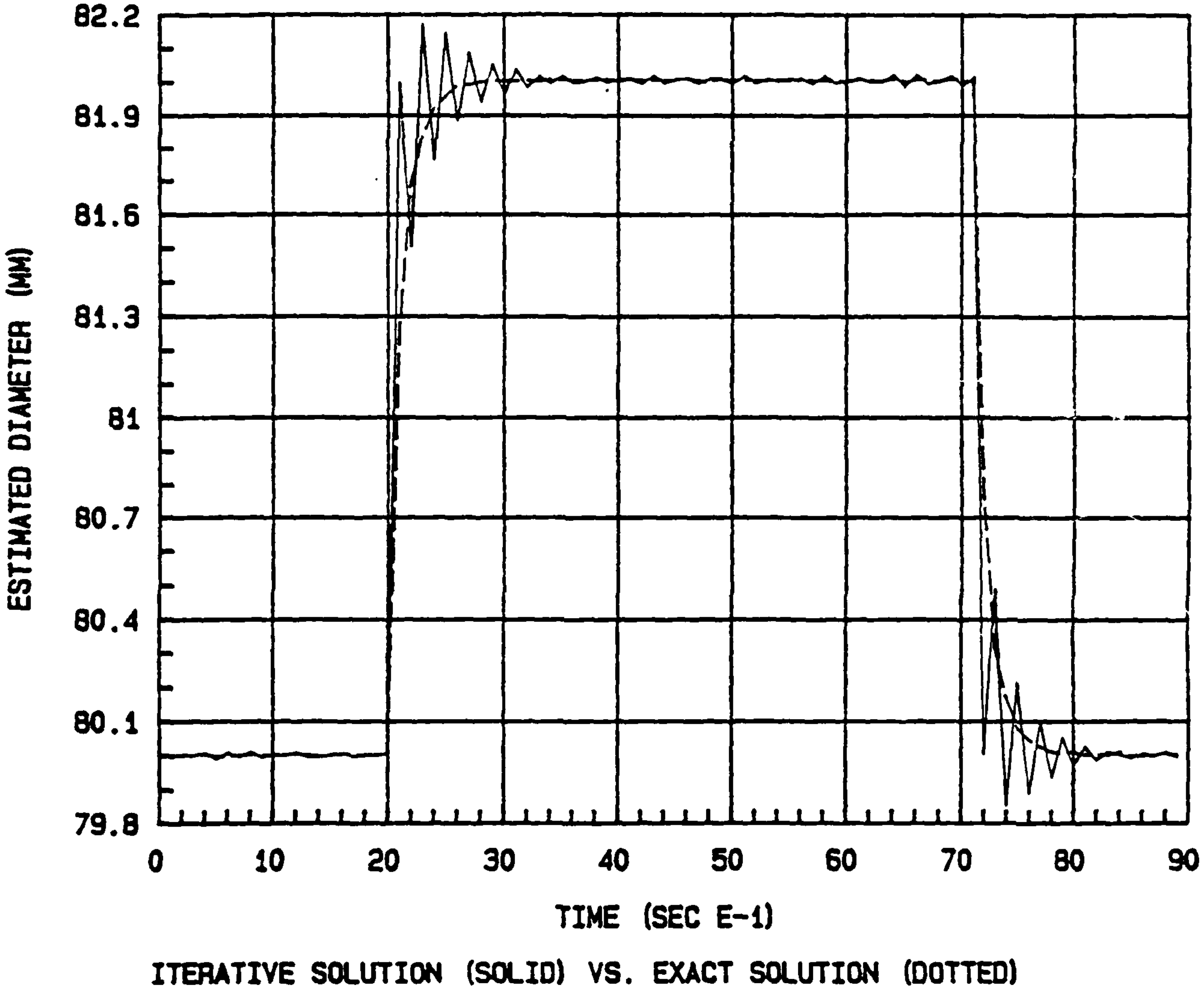


Figure 5. A comparison of the iterative and single-step solutions for the estimated diameter.

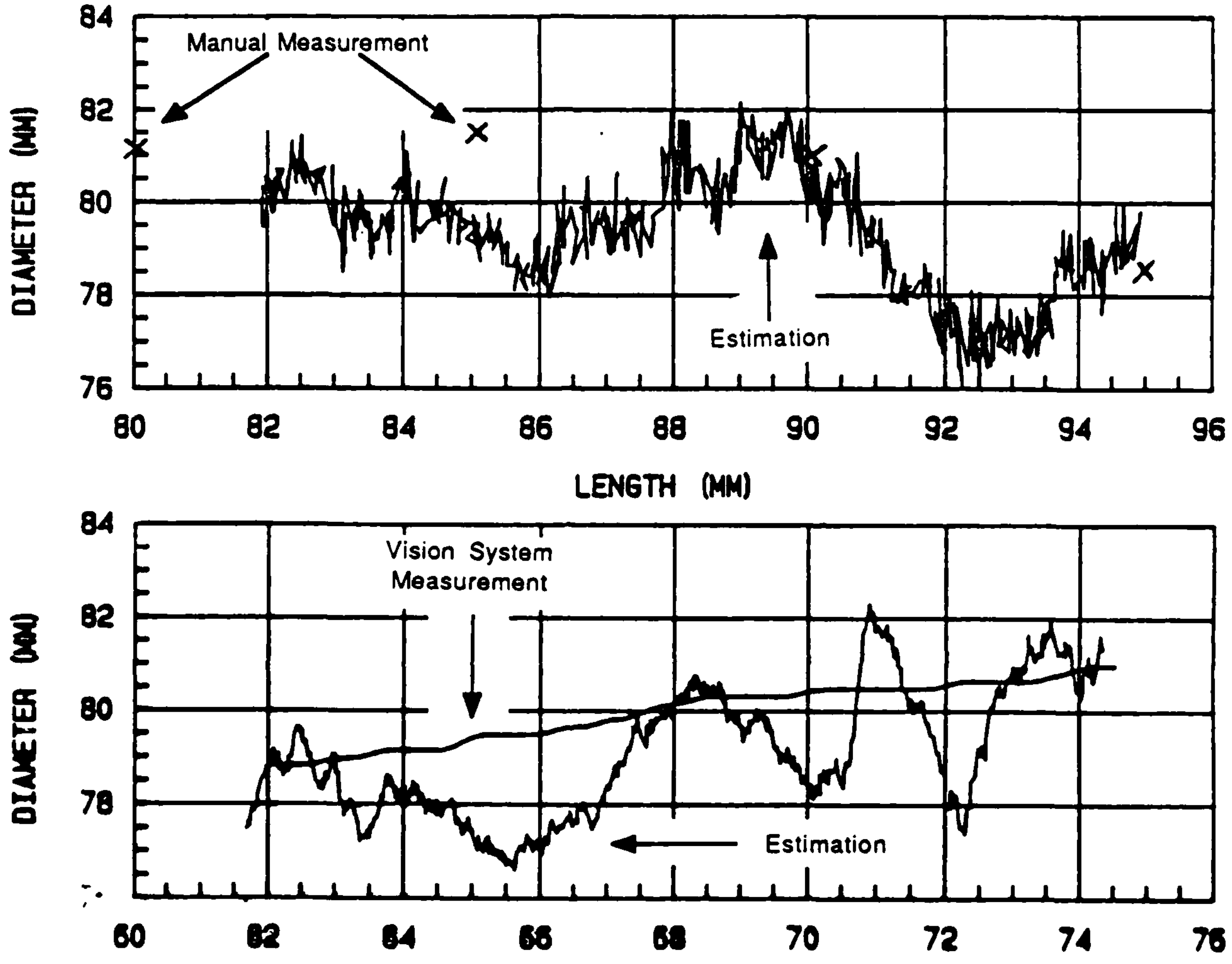
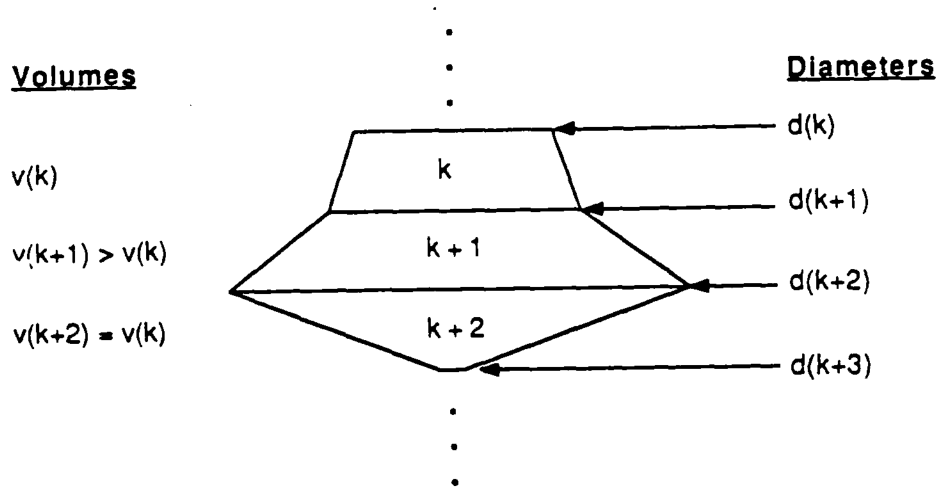
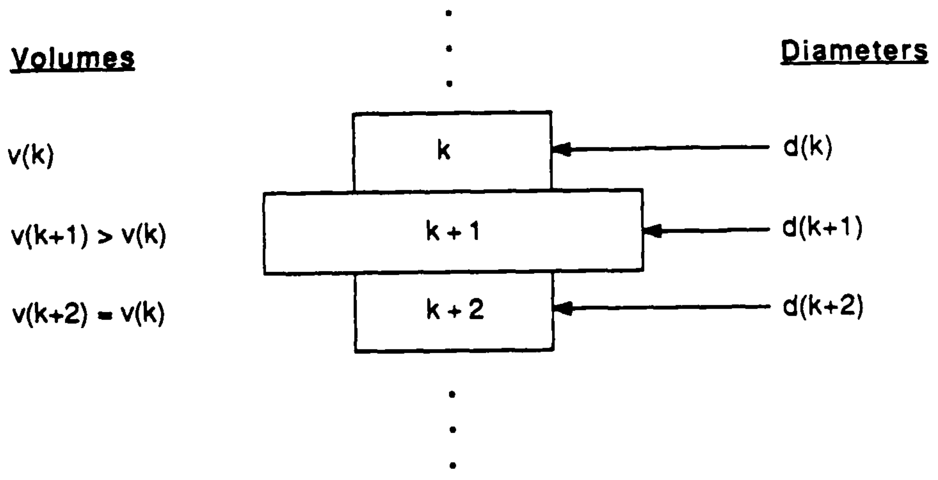


Figure 6. A comparison of diameter estimates using the iterative (top) and single-step (bottom) solutions; the diameter setpoint is 80 mm.



(a) The original representation.



(b) The revised representation.

Figure 7. The original and revised representations of crystal slices.

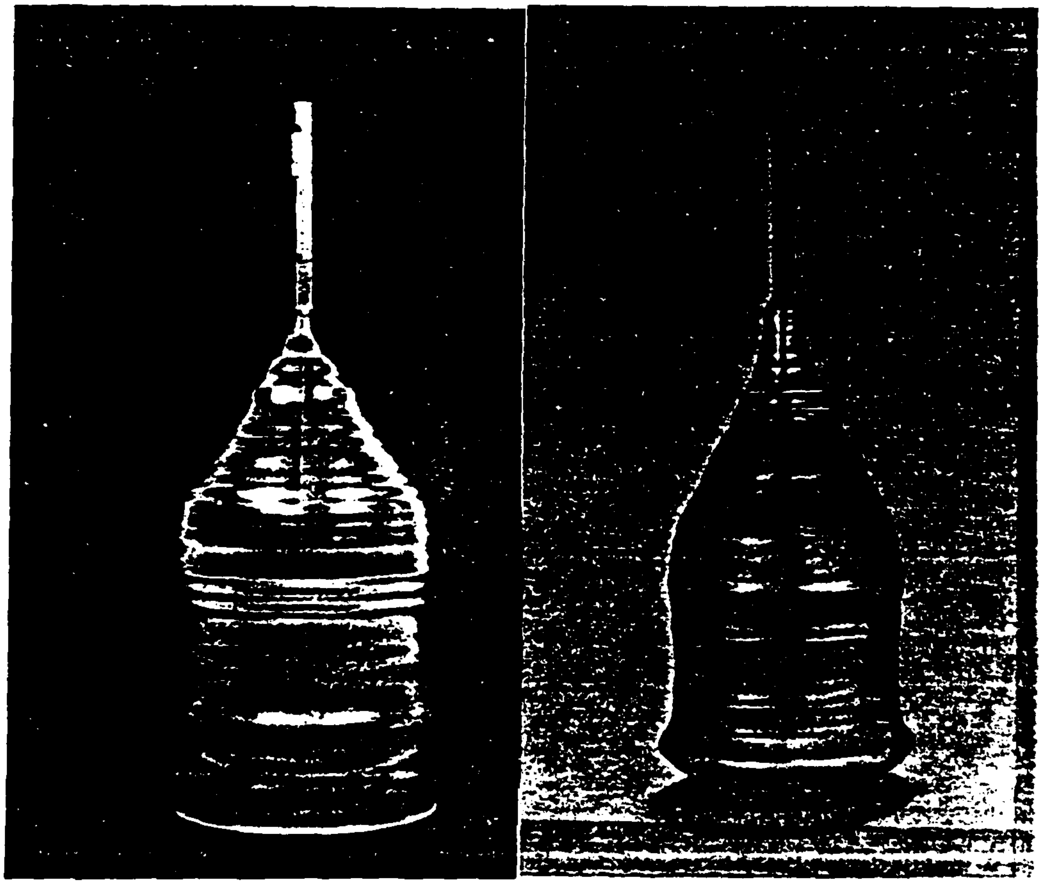


Figure 8. Two crystals grown consecutively under analog control.

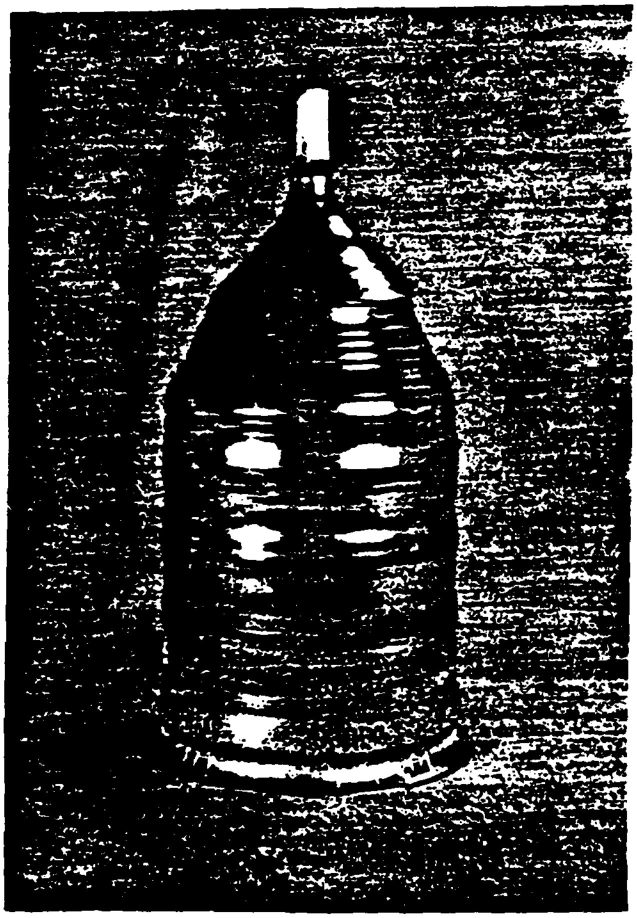


Figure 9. A crystal grown digitally without melt recession compensation.

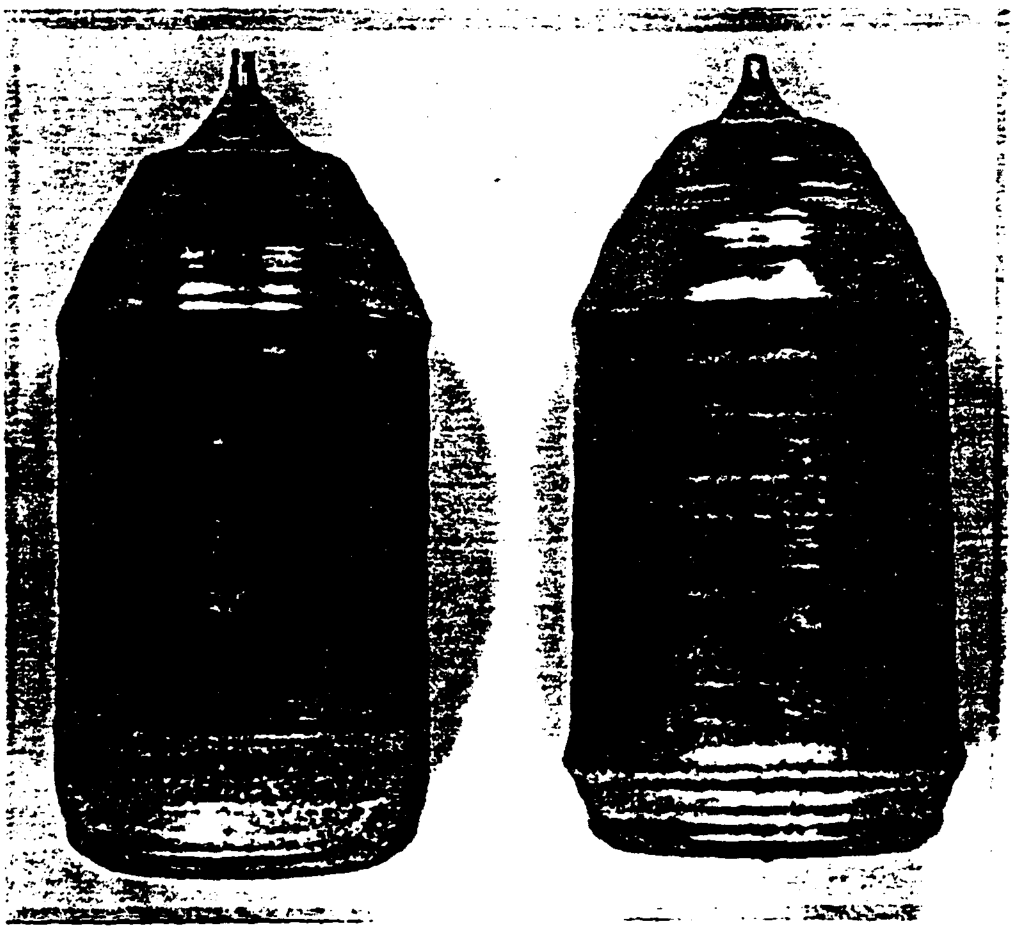


Figure 10. Two crystal grown digitally with melt recession compensation.

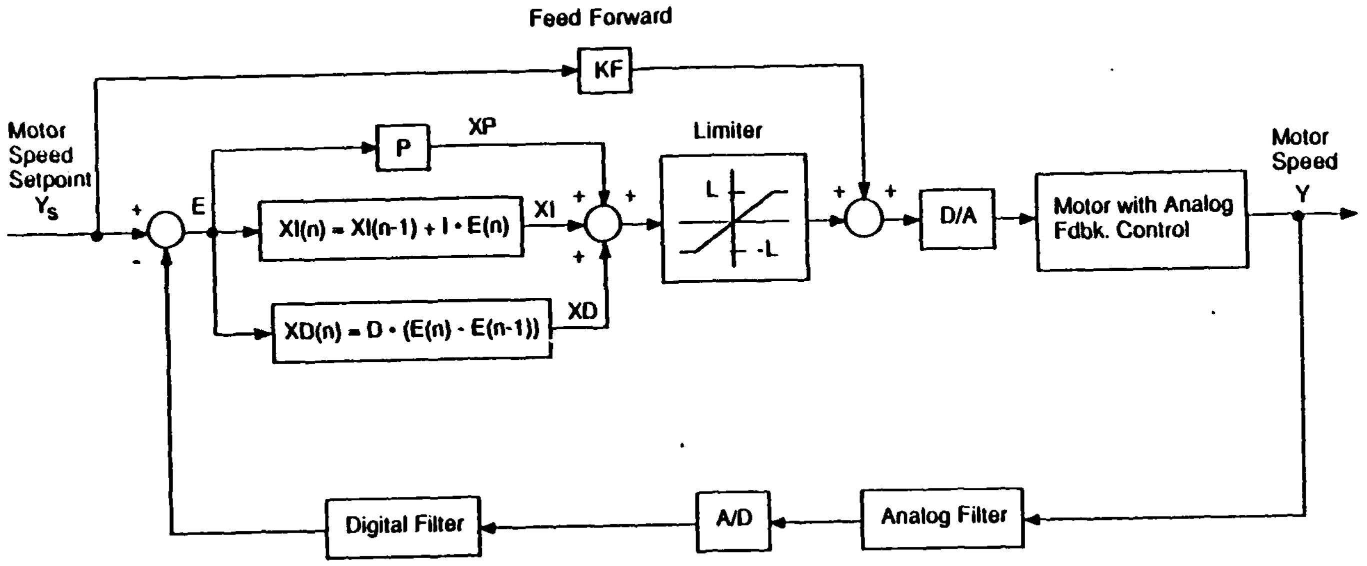


Figure 11. The motor control loop with a simplified diagram of the digital PID controller.