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Digital System for Monitoring and Controlling Remote Processes

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**ABSTRACT**

The need to operate increasingly complex and potentially hazardous facilities at higher degrees of efficiency can be met through the development of automated process control systems. The availability of microcomputers capable of interfacing to data acquisition and control equipment results in the possibility of developing such systems at low investment costs. In this paper, an automated control system is described which maintains a constant or time varying pressure in a pressure vessel. Process control, data acquisition and analysis is carried out using a commercially available microcomputer and data scanner interface device. In this system, a computer interface is developed to allow precision positioning of custom designed proportional valves. Continuous real-time process control is achieved through a direct digital control algorithm. The advantages to be gained by adapting this system to other process control applications is discussed. The modular design and ability of this system to operate many types of hardware control mechanisms makes it adaptable to a wide variety of industrial applications.

**INTRODUCTION**

The current trend in process control is towards more computer automation. Advances in microcomputers and digital peripheral control hardware has accelerated this trend [1]. The pressure controller described here was developed to reduce or eliminate human involvement in regulating the pressure in a test vessel. It is used to facilitate more accurate and repeatable transient pressure profiles in experiments with strict environmental requirements.

Modern process control technology has proven that the efficiency of plant operations is a function of how accurately the process system can be controlled. Often the process component which has the greatest influence on the overall system accuracy is a valve. Recent advances in automatic control valves have allowed for more sophisticated computer controlled processes [2].

In this system, the final control elements are a series of valves which provide direct digital control in throttling or modulating the process variable - high pressure gas or fluid. A digital positioning mechanism in the valve permits process flows to be controlled within sixty discrete increments of valve travel. With this accuracy and repeatability, operating parameters may be narrowed while, at the same time, insuring increased monitoring and control capabilities.

Control of a test pressure in a pressure vessel is chosen as an example to illustrate the application of this system; however, it is possible to adapt the hardware and software control mechanisms to a wide variety of industrial applications. Some examples are injection molding and extrusion process control, chemical manufacturing and temperature conditioning [3-5].

There has been increased attention focused on the development of expert systems for real-time control in industrial applications. Given a particular domain, such systems

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would use graphical displays of real-time performance data to provide operating personnel with knowledge-based advice on how to reach target conditions. In this manner, personnel with limited technical background are able to perform the work of process specialists. Through the addition of databases, this process controller can be expanded into the arena of expert systems.

The main driving force behind the development of this process control system was a series of weapon programs which require ocean depth simulation testing. Operator safety provided the initial impetus for building this system. Hazardous conditions often require that the monitoring and control be conducted remotely. This can be achieved by using fiber optics to link the host computer with the instrumentation and control hardware. It is also necessary to provide accurate and repeatable test environments. This made the system attractive from an operational standpoint.

## DEVELOPMENT OF CONTROL SYSTEM

### Hardware

Before the pressure controller was developed, the pressure vessel fluid flow regime was modeled. First an infinite pressure source at a constant pressure  $P_1$  was connected - through the control system - to the pressure vessel. The vessel had a time varying pressure  $P$ , some initial pressure  $P_0$  and there was no flow out (i.e. pressure losses) of the vessel. The governing differential equation for the gas flow into the chamber can then be written as:

$$dP/dt = f(t)(P_1 - P) \quad (1)$$

The general solution to this equation is

$$P(t) = P_1 + (P_0 - P_1)e^{-\int_0^t f(t)dt} \quad (2)$$

Where the boundary condition  $P(0) = P_0$  is used to determine the constant of integration. This function can be numerically integrated by replacing the integral with an approximating summation

$$f(t) = \sum_{i=1}^n a_i \theta(t - t_i) \quad (3)$$

In order to produce the proper pressure variation over time,  $P(t)$ ,  $f(t)$  must be a series of pulses of the proper magnitude ( $a_i$ ) and duration ( $t-t_i$ ).

This modelling exercise showed that the necessary control hardware consisted of variable flow mechanisms which are mounted in series with quick acting shut off valves. Figure 1 shows a schematic of the control system valve layout. Valves 1 and 2 were custom designed to provide the necessary orifice sizing. The ability to develop these custom valves, by combining a mechanical ball valve with an electrical positioning actuator, was the key to achieving automated and precise flow control without sacrificing system flexibility.

In order to achieve a large flow capacity, 1/2 inch quarter-turn ball valves were used (Jamesbury Inc.). These valves give reliable and tight high pressure seals, are readily adaptable to pneumatic or electric actuators and are well suited for flow throttling. A bi-directional, electrically operated, rotary actuator (Fox/Jordan Inc.) was then

mounted on each ball valve to mechanically rotate the spherical control element. The actuator has a 120 volt AC motor which responds to a 4 to 20 mA DC command signal. By varying the current command signal, it was possible to vary the actuator motion and achieve a particular flow orifice. Figure 2 is a photograph showing the rotary actuator - with its protective cap removed - attached to the quarter-turn ball valve.

This configuration produced a proportional control valve which responds directly to digital command signals. An optical shaft encoder provides a feedback signal which indicates the valve plug position. This allows the valve to control flow rate and pressure with the accuracy and repeatability of the digital computer. Its only drawback is the slow response time which is inherent in the design. The stepping motor cannot reach high speeds immediately when started and will overshoot if not decelerated from these speeds. Therefore, acceleration and deceleration (ramping) is provided to assure reliable stepping and maintain positioning accuracy. Since the system application could not tolerate the slow response time that this ramping produced, a quick acting open/close solenoid valve was placed upstream of each proportional solenoid (valves 6 and 7 in Fig. 1). These valves provided a response time of approximately 50 ms.

An additional quick acting open/close solenoid (valve 3) was mounted on another outlet port to allow for extremely rapid venting without the fine throttling capabilities. Several fail-safe mechanisms were added to prevent overpressurization in the event of control system failures. Two three way solenoids (valves 4 & 5) were added to the high pressure inlet lines. Under normal operating conditions these valves allow flow into the pressure vessel. If a power loss occurs at the host computer or at the test facility, the ports in valves 4 and 5 change to simultaneously stop the inlet flow and allow the vessel to vent its pressure.

The heart of the digital control system, which sends the command signals to the appropriate valves, is a Hewlett Packard data scanner and microcomputer. Closed loop feedback is achieved by using an analog strain gage type pressure transducer which monitors the vessel pressure. In this system, the data scanner contains the following control cards:

1. AC voltage relay cards used to direct power to the quick acting solenoid valves (valves 3 through 7).
2. 4-20 mA current supply card used to provide the modulating current to the proportional ball valves (valves 1 & 2).
3. Guarded acquisition card used to receive signals from process monitor and/or control transducers.
4. Analog-to-digital conversion card to accommodate analog transducers and data acquisition (e.g. strain gages).

The application of high pressure with possible energy levels in excess of 20 million ft. lbs. and also the testing of units containing high explosives made remote control a necessity. When dealing with energy levels of this magnitude "remote" does not mean a barricaded control room but rather a control room which is located in a separate building outside a precalculated hazard radius.

It was found that fiber optics provided the simplest means for connecting the host computer to the control hardware and vessel which were located over a half mile away in the test cell. Figure 3 shows a schematic of the control hardware including the fiber optic link. A fiber optic remote control system offers a number of desirable features such as precise and rapid measurements of a number of components and the ability to operate in high temperatures, pressures and radiation fields. Fiber optic cable does not have the resistance buildup problem associated with long lengths of wire cables. As a result, there is no signal attenuation or need for larger diameter cables. Fiber optic cable is also free from cross talk and ringing because it is immune to the electrical noise created by plant machinery [6].

Information was transferred through the two fiber optic lines (one transmit, one receive) in a serial form while the host computer and data scanner processed parallel data. In order to achieve the proper communications link, two extender boxes were connected to each end of the fiber optic cable. They performed the proper translations of HPIB parallel information into serial format and vice versa. Figure 4 is a photograph of the test lab layout which shows the control hardware, pressure vessel and host computer.

### Software

The software package for this system was developed in-house with both ease of operator use and control capabilities in mind. It uses a series of intelligent menus to enable or disable the controller, to change its mode (manual or automatic), and to enter the process setpoints and tuning parameters. Figure 5 shows a flowchart of the software used to set up the control system.

All of the parameters from a previous test are stored in data files and are recoverable. This avoids the need to reenter duplicate information. If a new process is carried out, the user must choose to control the pressure levels manually or to let the computer conduct an automated test. Manual mode uses a series of "softkeys" on the computer keyboard to actuate the valves; this will be discussed in more detail later. Next, the user supplies the tuning parameters for the feedback pressure transducer, proportional valve plug positioning, data acquisition and the allowable error (tracking) band for the automated control algorithm. Finally, the desired transient pressure profile is defined through a series of menu driven commands. Most of the tests in this lab require various pressurization and depressurization rates with a particular hold time at the maximum pressure; however, very complex profiles can be programmed into the software by using the X-Y tabular data input format or by specifying a math function. After all of the proper tuning parameters have been loaded into the driver routine, the control loop software is executed.

The control loop software (see Fig. 6 for flowchart) sends all of the appropriate messages to the data scanner. The scanner, in turn, actuates the valve system so that the vessel is pressurized according to the user specified pressure versus time profile. Upon entering the control loop subroutine, the valves are set so that the vessel pressure is vented to 0 psi. Then an initial pressure transducer reading is taken and is thereafter used as the voltage corresponding to zero pressure.

At this point, the special softkeys are defined and their function is shown in reverse video at the bottom of the CRT display. Each key is programmed to transfer execution to various control loops within the subroutine. In this manner, the operator can actuate the valve system by pressing any of the keys. For example, if softkey PF1 is pressed, the inlet proportional valve begins to open and will continue to do so until the key is released. Softkey PF2 reverses this process and causes the inlet orifice to gradually reduce. If the user chooses to control the process by pressing the 16 softkeys, then this is termed "manual" operation.

If the user chooses "automated" control mode then the proportional valves are set to the user specified orifice. The computer will then control the remainder of the test. Continuous real time process control is achieved through a digital control algorithm which provides system compensation to eliminate poor transient response and increase steady-state accuracy. The system responds to the process variable (pressure) by determining the error (deviation from setpoint) and adjusting the output signal (control variable) based on the process error over time.

The computer will actuate the on/off valves as necessary in order to follow the preprogrammed pressure profile. If the process profile begins to travel outside of the specified allowable error band, then the computer makes adjustments to the inlet or outlet flows. The software uses a derivative control algorithm which determines an error based on the slope of the pressure profile. This makes the control scheme forward-looking with the ability to anticipate future excursions outside of the desired error band. As an additional safety precaution, all of the softkeys are given interrupt priority during an automated execution. This gives the operator the capability of switching to manual control at any time during the test. When the process has gone through the desired number of cycles the data is stored on disk for future reference and each cycle is plotted.

## SYSTEM PERFORMANCE

### Manual Control

This system was first applied to the W88 stockpile-to-target pressure test and was operated in a manual mode. The weapon assembly was placed in a 40 inch diameter by 10 foot long cylindrical vessel. The vessel was partially filled with water to reduce the energy content and an air volume of 14 cu.ft. was pressurized with 2000 psi nitrogen gas bottles (pressure source to control system).

Figure 7 shows the actual pressure versus time in the vessel along with the desired pressure profile (dotted line). It can be seen that the system was able to track the desired process with only slight deviations from the specified setpoints. Another successful application of the manual control mode is shown in Figure 8. It should be noted that a hold time, corresponding to a dwell at maximum pressure, is printed in the upper right hand corner of the final plot. During a hold, a continuously updated digital pressure readout is printed to the screen but the plotting is halted. When the user releases the system hold, real-time screen plotting continues as before. It is impractical to plot the slight pressure fluctuations during a pressure hold because of the long time periods associated with hold times. If the time base was stretched out long enough to accommodate plotting of a relatively long hold time, it would obscure the more important parameters- pressurization and depressurization rates- and significantly reduce the screen plot resolution.

### Automated Control

A number of sample runs were conducted to test the capabilities of this system in automated control. In this mode, the on/off solenoid valves play a more important role in the flow control. Figures 9 and 10 show two examples of computer regulated processes which followed the desired pressure profile (within the allowable error band of  $\pm 5\%$ ). As the on/off solenoid valves actuate, the resulting pressure pulses cause a step wise shape in the vessel pressure profile. If for any given external environment, the proportional solenoid valves are preset to the proper position, the process setpoint will be achieved without the assistance of the on/off solenoids. The depressurization in Fig. 10 is an example of this phenomenon.

### System Response

There are many factors which influence the response of this control system and its ability to meet the required process setpoints in the required time frame. These include temperature, mechanical loading and hysteresis. The pressure controller must be complex and flexible enough to compensate for these and other effects. However, while this is desirable from an operational standpoint it is not altogether feasible. The factors which are anticipated to occur most often can be considered during the hardware and software development. In addition a robust controller will withstand some unforeseen

events but other factors must be compensated for through the use of judicious external modifications and hardware adjustments.

Following is a list of the major factors which influence the response of this pressure control system:

1. total inlet and outlet flow capacity
2. driving force pressure and volume (inlet energy)
3. fluid medium (compressibility effects)
4. fine adjustment capabilities of proportional valves
5. response time of solenoid valves
6. signal transfer time
7. execution speed of control computer

With this partial list of factors which influence the control capabilities, it is easy to see that for any given external environment, the system will have some operation envelope. It will be unable to adequately control processes which require it to operate outside of this envelope. For example, it may be impossible to bleed the pressure from a vessel at the desired rate if the maximum outlet orifice is too small. However, by adjusting some variables (e.g. source pressure level, outlet orifice), it is possible to compensate for deficiencies in other variables. This, in turn, allows the operation environment to be shifted and creates a very flexible control system.

## APPLICATIONS IN INDUSTRY

Control of the transient pressure in a vessel is chosen as an example to illustrate the application of this system; however, it is possible to adapt this system to a number of process control applications. The hardware employed in this system is a series of solenoid valves but any mechanism which can be controlled with an AC or DC voltage relay or a 4-20 mA variable current will plug directly into this system. A pressure transducer is used to supply the feedback signal to the computer but any transducer (e.g. load, displacement), thermocouple or strain gage can be substituted as the control variable.

One of the key elements to economical operation of chemical plants is the operating efficiency of its compressors. This efficiency can be achieved by maintaining the optimum balance between pressure and flow. Damage to the compressor and/or dangerous process conditions can result if the compressor surges. That is, if a pressure increase is accompanied by a flow decrease. By combining compressor performance algorithms with real-time control, it is possible to operate close to peak efficiency without the risk of forcing a compressor into surge.

Supervisory systems such as this could also be applied to the operation of combustors in gas turbine power generation. It can introduce combustion and vane cooling air flows into the combustor, adjust the liquid fuel injections and control the backpressure to hold the combustor pressure at setpoint.

Injection molding provides yet another application of this type of process control system. The operating principle of an injection molding machine is shown schematically in Figure 11. The important parameters for injection molding are the internal mold pressure, the product temperature and the clamping pressures on the mold. The great demands placed on injection molded articles make them subject to strict quality assurance programs. It is therefore necessary to monitor and control the important variables in order to assure the proper formation of a molded article. In addition, excessive pressures may buckle the mold and result in unwanted flash on the article. This produces waste and rejects.

Other applications of this automated process control system can be found in the following industries:

1. Production of gases in batch-type microreactors where it is necessary to minimize pressure fluctuations and to carry out data acquisition in exact sampling intervals [7]
2. Extrusion of plastics where real-time control is needed to maintain optimum extrusion screw speed, as well as, temperature and pressure at the screw tip
3. Optimizing composition and physical properties of reacting materials to improve the quality of manufactured chemicals [8]
4. Monitor and adjust furnace temperatures in the production of electronic components.

## CONCLUSIONS

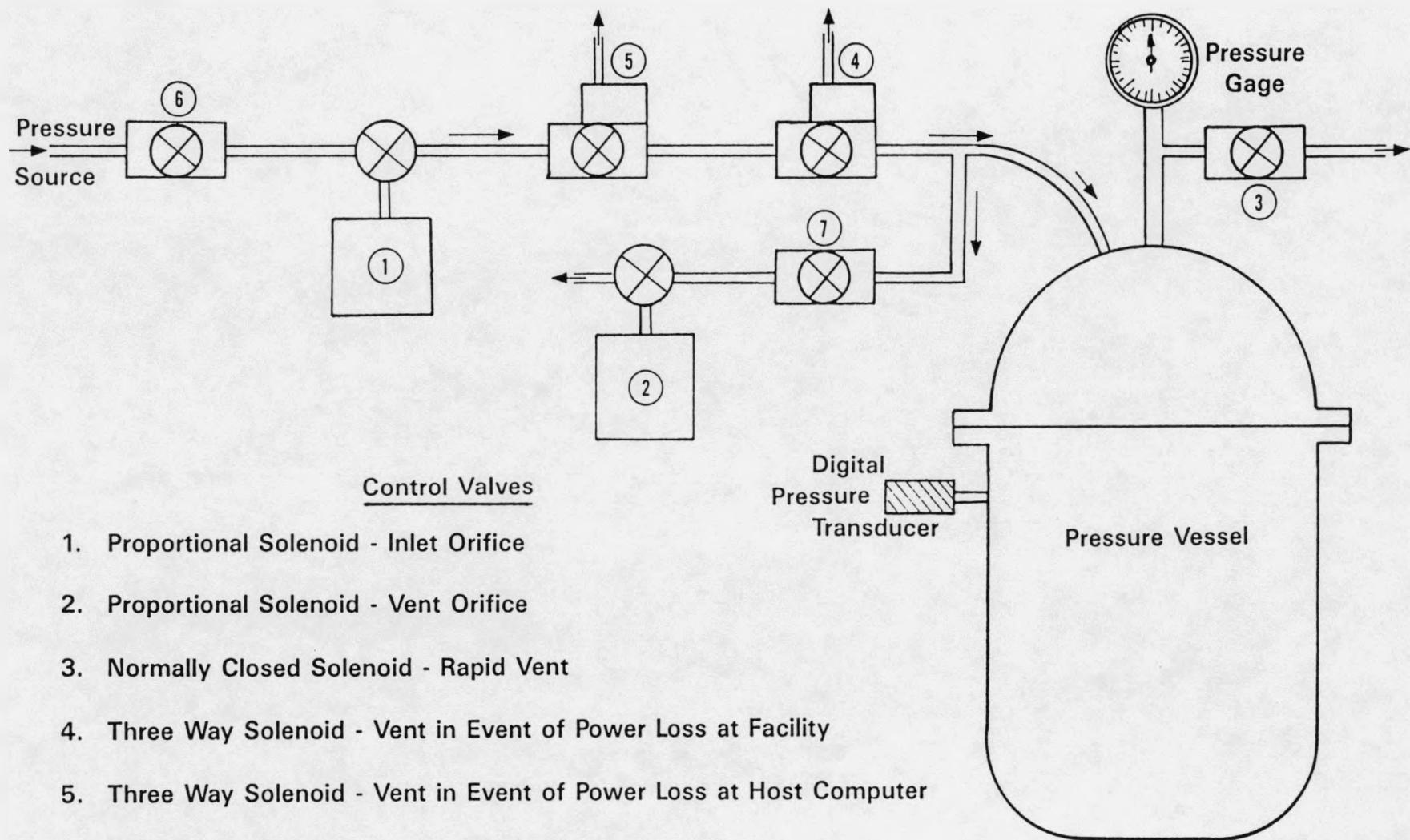
This paper describes an automated control system which maintains a constant or time varying pressure in a pressure vessel. Improvements in microcomputers and peripheral control hardware has made it feasible to develop such systems at low investment costs.

Custom designed proportional solenoid valves were employed to provide the accurate and repeatable flow control necessary for the automated operation. The control software uses a series of logical decision loops which are shaped by preprogrammed information. A digital feedback control loop is employed to maintain the desired pressure versus time profile. By connecting various control mechanisms and making software modifications, it is possible to adapt this system to a wide variety of industrial applications.

The increased emphasis on improved and repeatable production quality requires that processing plants optimize their processes and maintain close tolerances on the operational characteristics of the plant. Towards that end, automated control systems, such as the one described here, are receiving increased attention. They provide a very flexible and capable package for remotely supervising, monitoring and controlling complex processes. This is essential to achieving better process control with improved product quality.

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Control Valves

1. Proportional Solenoid - Inlet Orifice
2. Proportional Solenoid - Vent Orifice
3. Normally Closed Solenoid - Rapid Vent
4. Three Way Solenoid - Vent in Event of Power Loss at Facility
5. Three Way Solenoid - Vent in Event of Power Loss at Host Computer
6. Normally Closed Solenoid - Automated Inlet Control
7. Normally Closed Solenoid - Automated Outlet Control

**Figure 1 : Schematic of Control System Valve Layout**

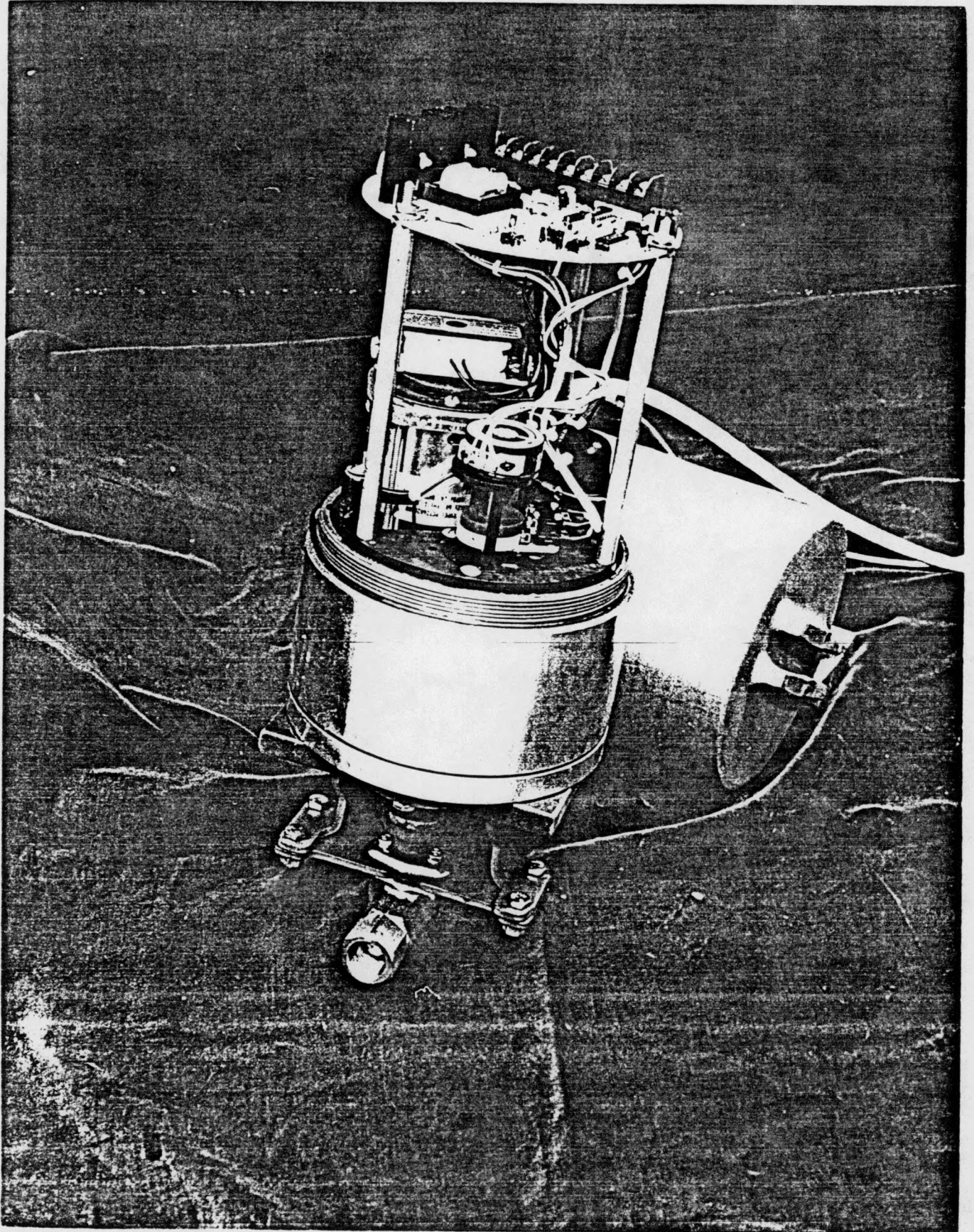


Figure 2 : Current Controlled Proportional Solenoid Valve

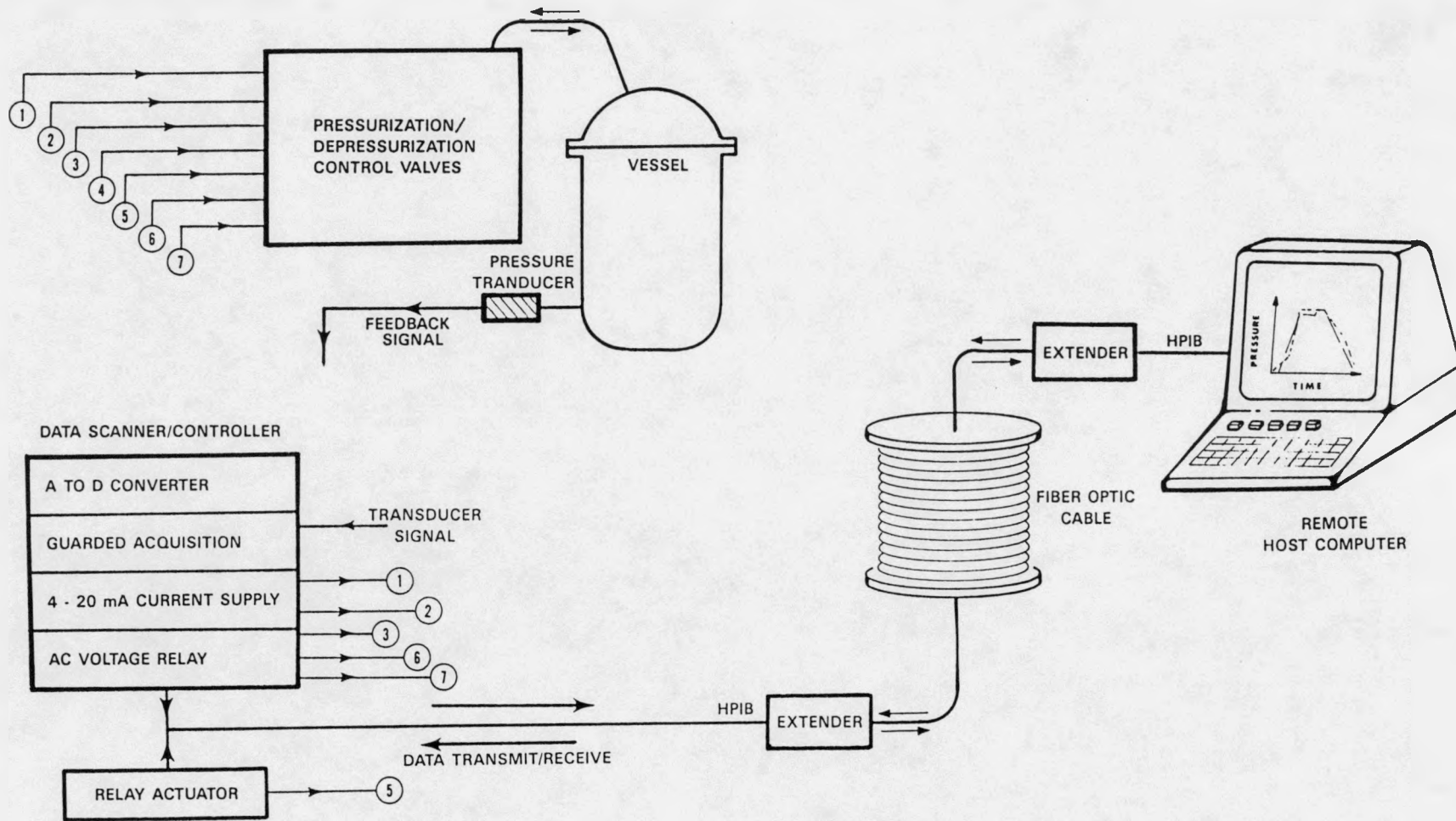
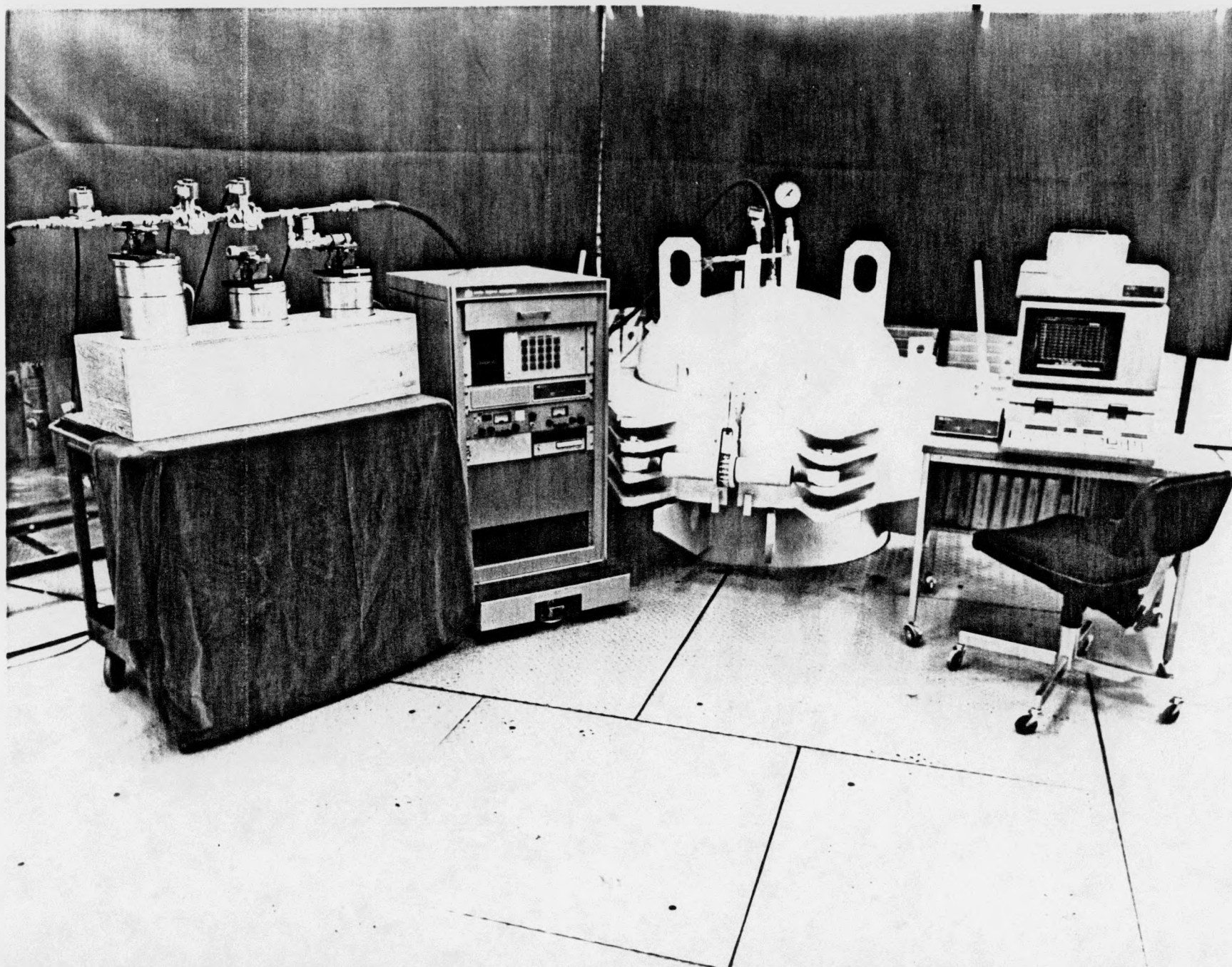


Figure 3 : Linking Control Hardware and Instrumentation to Host Computer



**Figure 4 : Pressure Control Hardware, Test Vessel, Data Acquisition System and Host Computer**

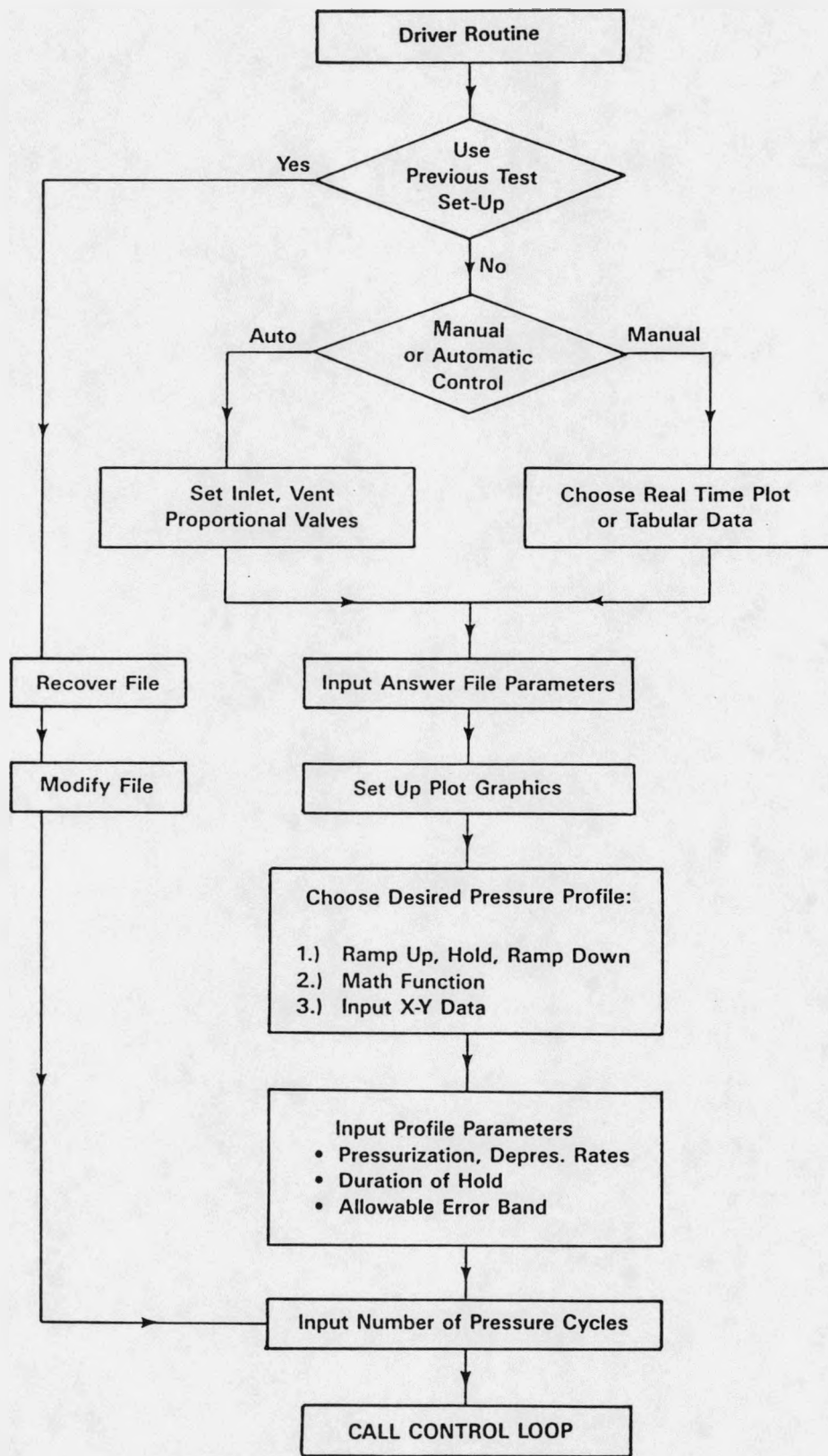


Figure 5 : General Flowchart for Tuning Parameter Entry

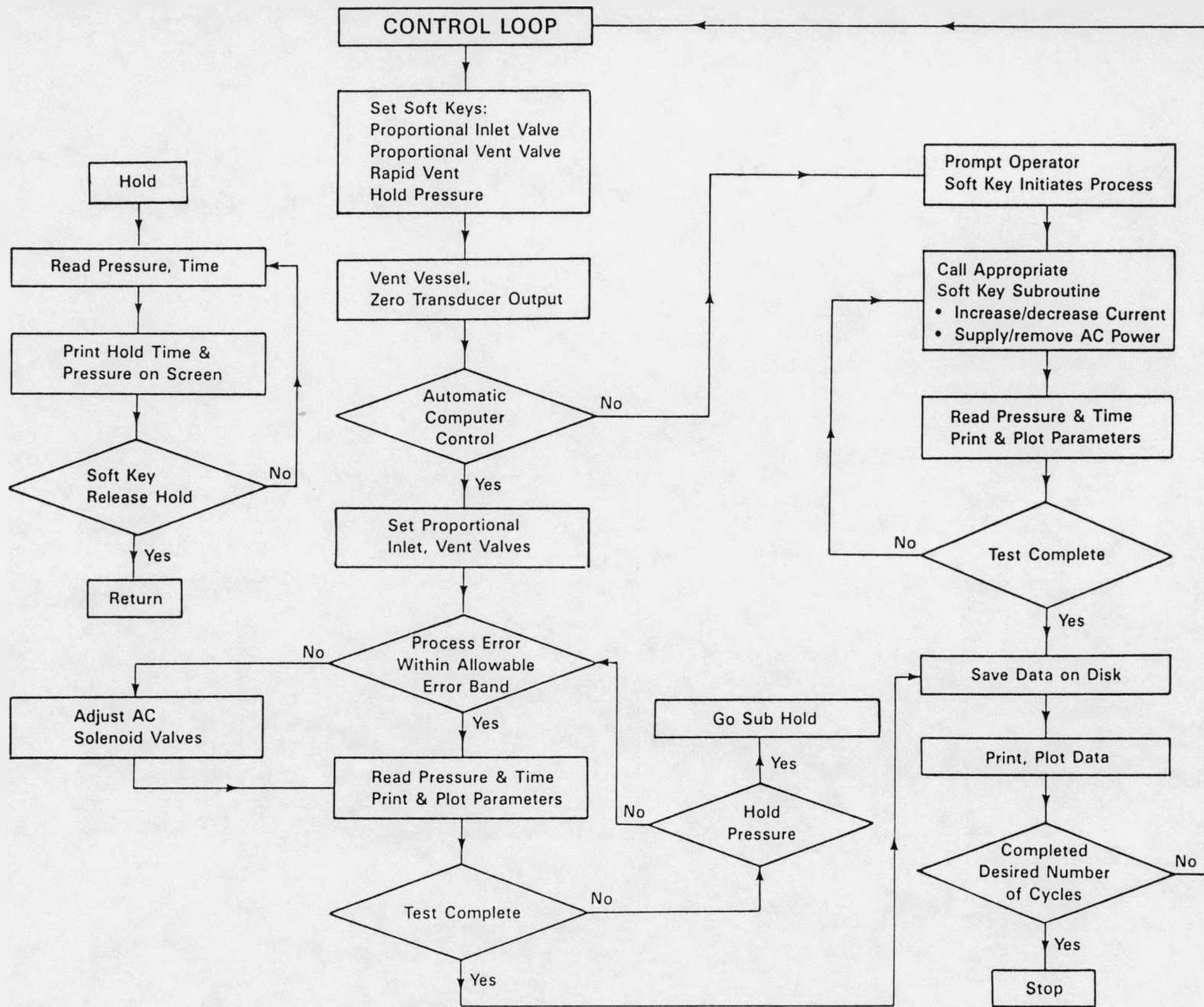


Figure 6 : Flowchart for Automatic Pressure Control Software

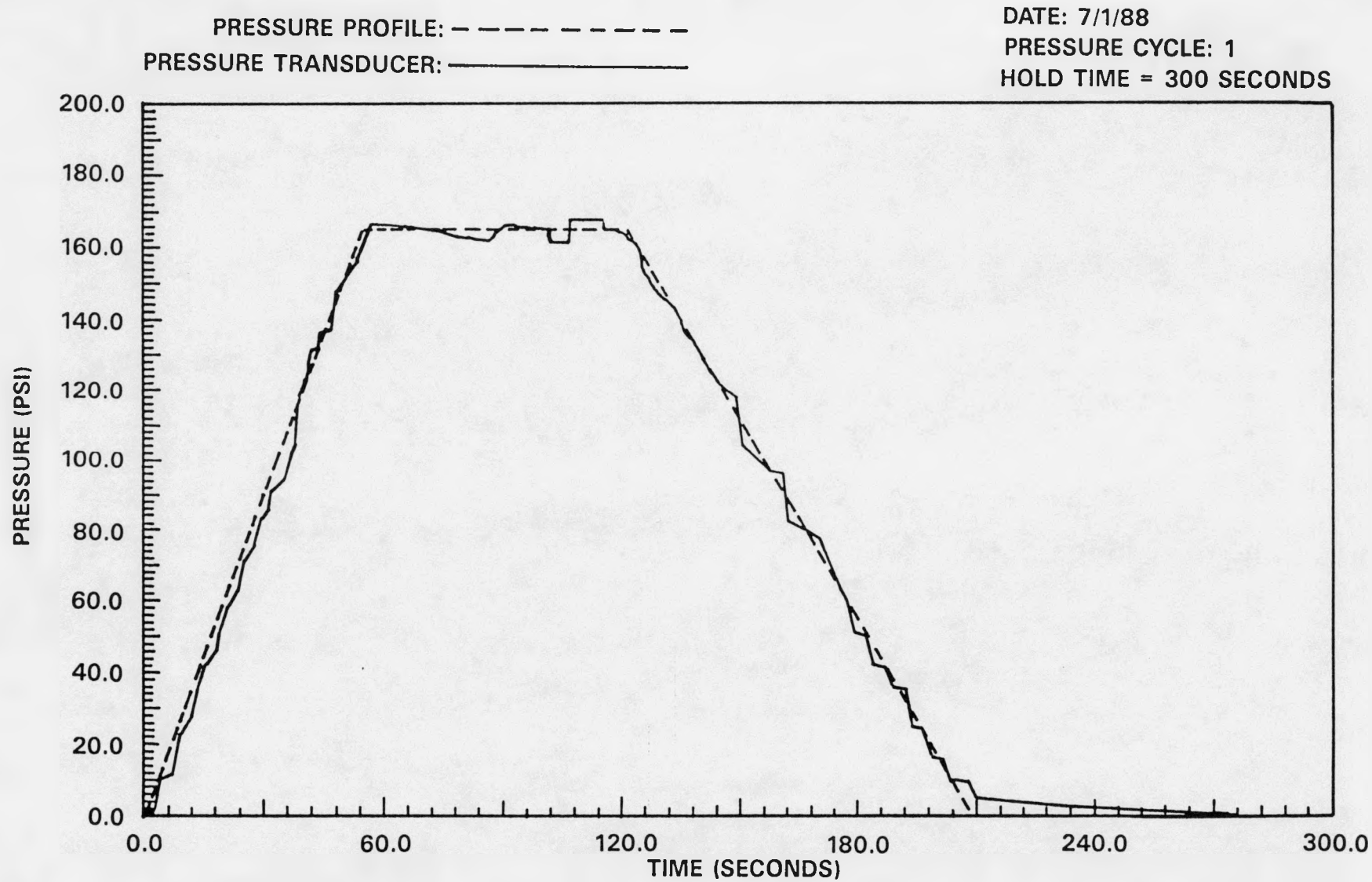


Figure 7 : Pressure Profile for W88 Stockpile-to-Target Pressure Test

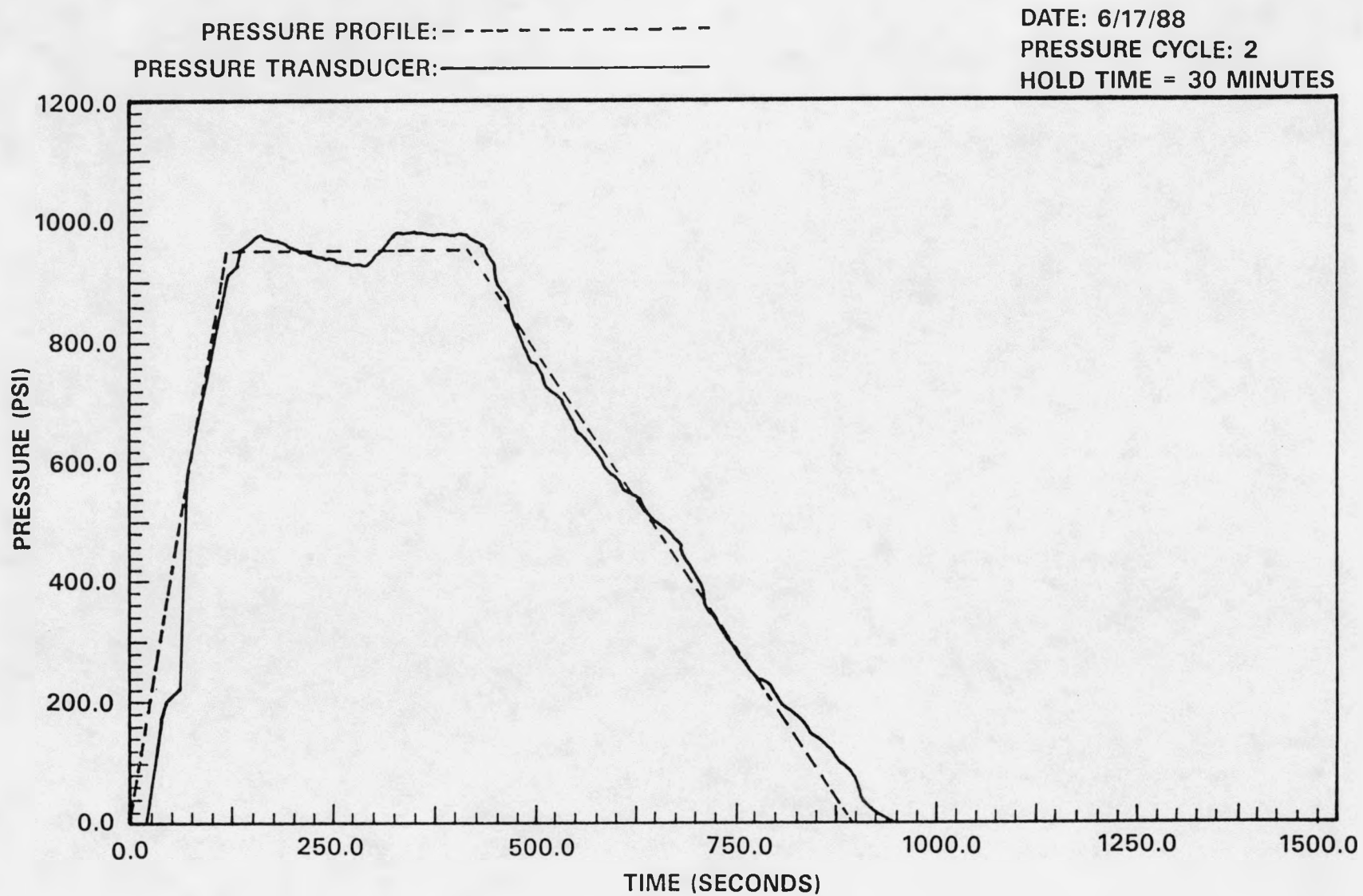


Figure 8 : Sample High Pressure Profile with Computer  
in Manual Mode

PRESSURE PROFILE: - - - - -  
PRESSURE TRANSDUCER: \_\_\_\_\_

DATE: 10/8/88  
PRESSURE CYCLE: 2

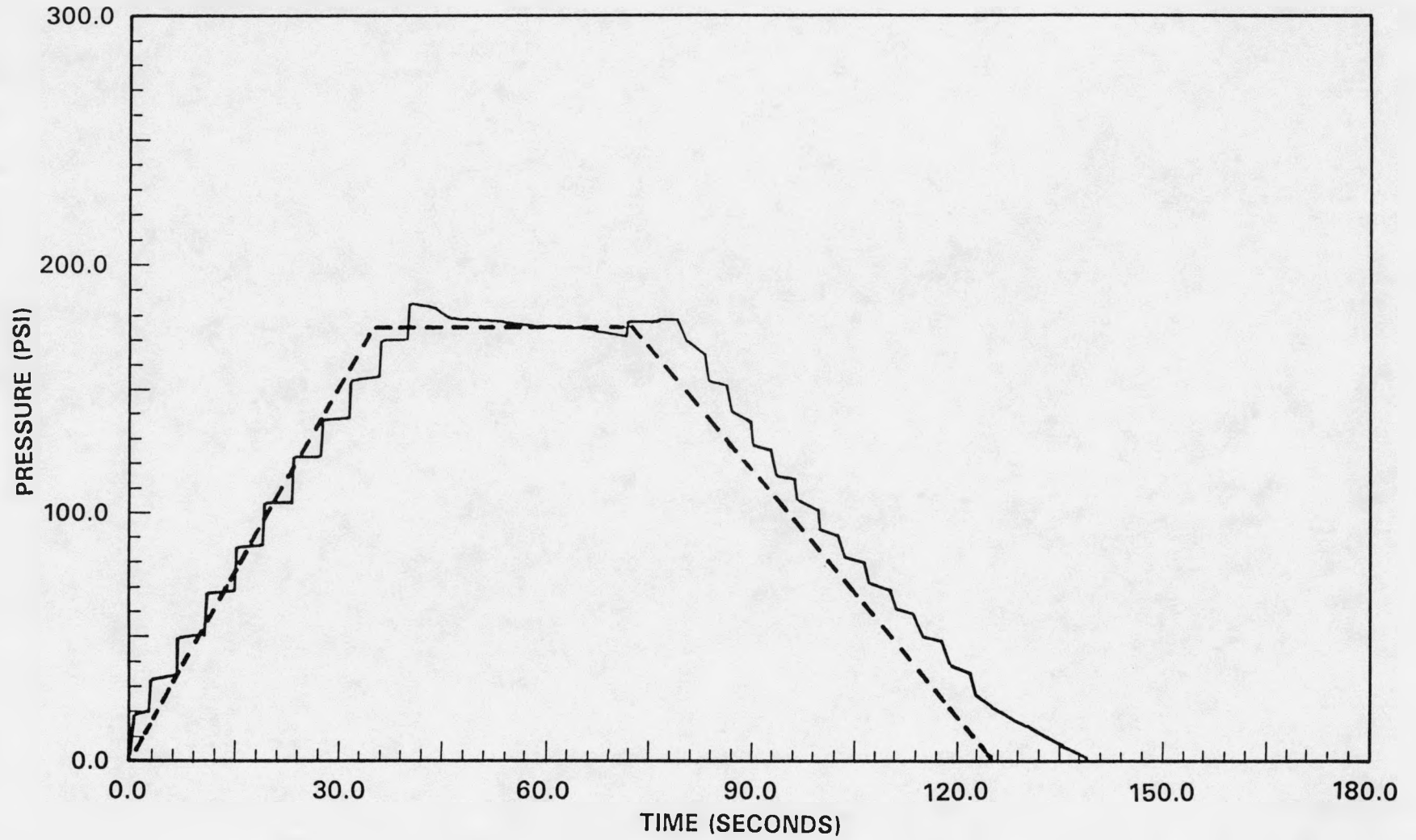


Figure 9 : Pressure Profile Using Automated Process Control

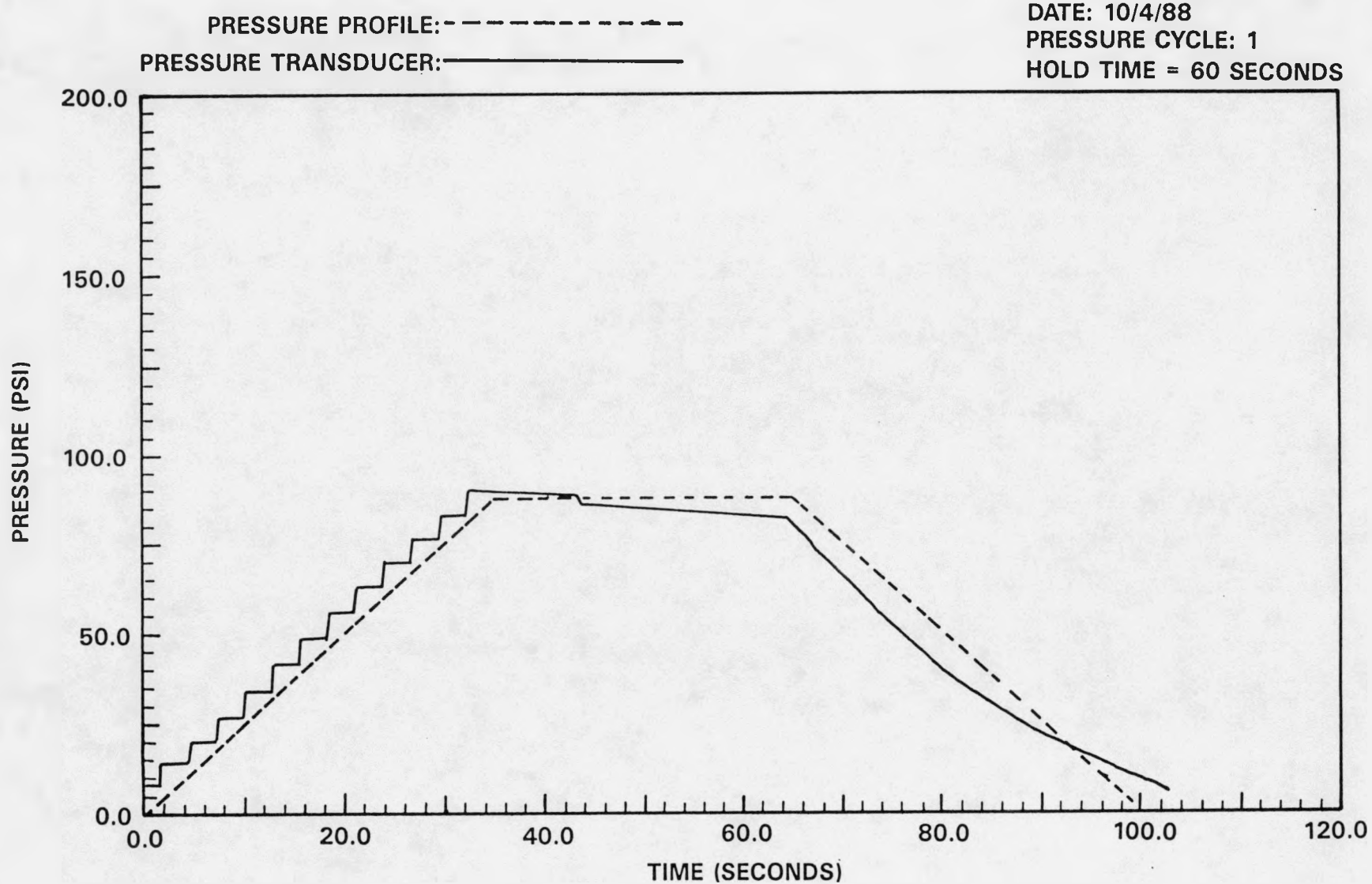
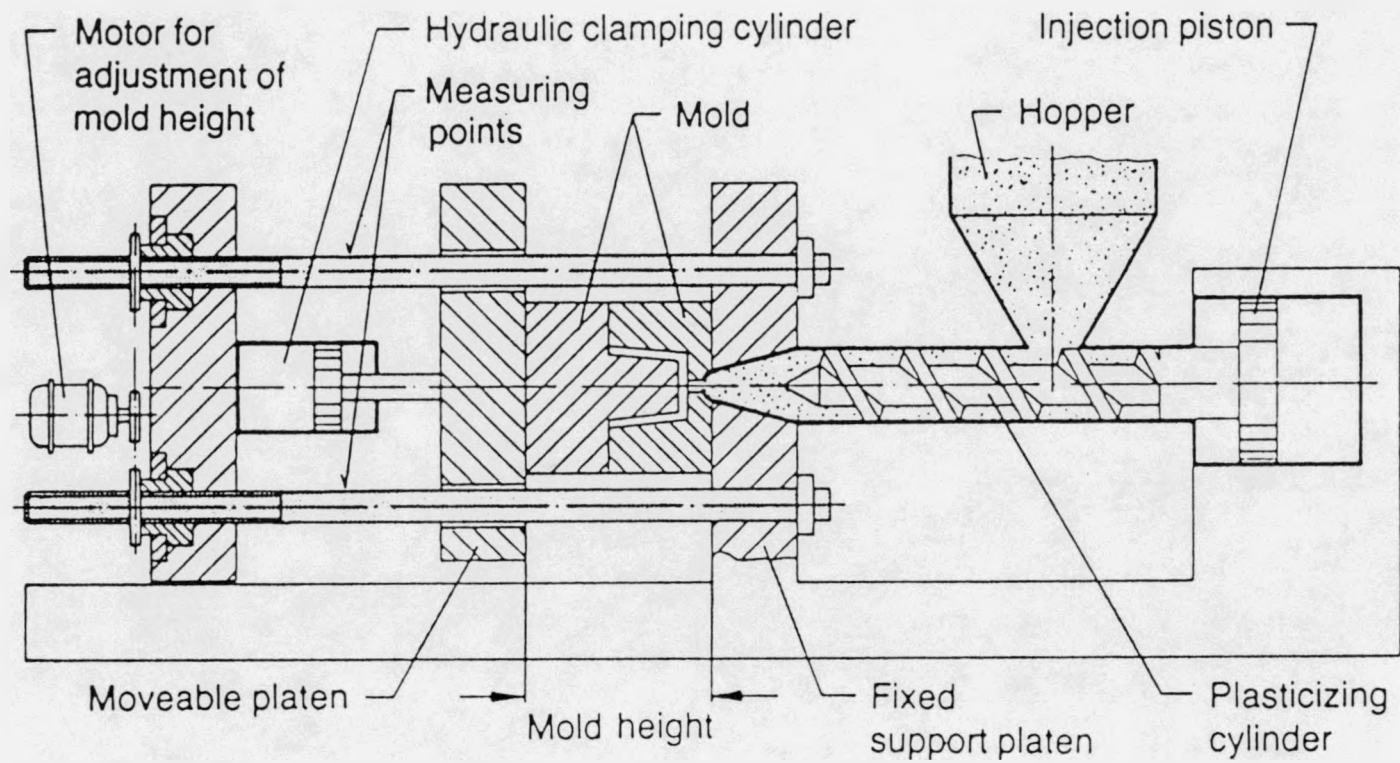


Figure 10 : Computer Automated Pressure Cycle



**Figure 11 : Principle of an Injection Molding Machine**