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APPLICATIONS OF A DOWNHOLE PROGRAMMABLE MICROPROCESSOR FOR A GEOTHERMAL BOREHOLE INSPECTION TOOL

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ABSTRACT

The high-temperature scanning borehole inspection system is currently being developed jointly by the Los Alamos National Laboratory (LANL) and Westfalische Berggewerkschaftskasse (WBK) of West Germany. The downhole instrument is a digital televiewer that utilized a microprocessor to digitize, process and transmit the acoustic information to the surface acquisition and control system.

The primary operation of the downhole acoustic assembly uses a piezoelectric crystal acting as a receiver-transmitter which is mounted on the rotating head. The crystal emits a burst of acoustic energy that propagates through the borehole fluid with a portion of the energy reflected by the borehole wall back to the crystal. The time of travel and the amplitude of the reflected signal are conditioned by the microprocessor and transmitted along with other pertinent data to the surface data processing center.

This instrument has been designed specifically for use in geothermal borehole environments to determine the location of fractures intersecting the borehole and provide information concerning overall borehole conditions. It may also be used for definitive casing inspection. The instrument essentially eliminates operator interaction for downhole control and simplifies assembly and maintenance procedures.

INTRODUCTION

Borehole televiewers have been used successfully to measure the physical properties of the borehole environment for some time. In essence, analog borehole televiewers utilize a high-frequency piezoelectric crystal as a transmitter and receiver to scan the borehole wall with bursts of acoustic energy. The reflection of the acoustic burst varies in amplitude as a function of the distance and the physical properties of the wall itself. The reflected signal is then amplified, bandpass filtered and the low-frequency envelope together with north orientation are transmitted to surface.

At the surface the analog reflected signal envelope, north pulses, and depth information are fed to an oscilloscope or moving wire-type recorder to display the data in real time. The data may also be stored on analog magnetic tape for later processing.

A Borehole Acoustic Televiewer (BAT) designed specifically for geothermal environments is presently being developed by the Los Alamos National Laboratory's Geophysical Instrumentation Group in collaboration with WBK in West Germany. The BAT tool is a digital televiewer which utilizes a downhole microprocessor to digitally process the data downhole and transmit reduced data to the surface via PCM formatted wave train.

SYSTEM DESCRIPTION

The BAT system consists of the downhole tool and the associated surface processing equipment. The downhole section is broken down into three segments. The acoustic subassembly contains the crystal transducer, fluxgate magnetometer, slip ring assembly, and ac motor (Fig. 1). The acoustic subassembly is housed in an oil-filled pressure equalization cavity that allows the tool to be operated at elevated temperatures and pressures. A new thermal protection assembly consists of a special dewar and heat sink to house the electronic package. This thermal protection system permits continuous operation of the electronics for a period of six to eight hours in wellbores where fluid temperatures approach 300°C.

The receiver-transmitter module houses all the components required to support the rotating crystal head and provide the necessary position parameters. One high-frequency (1.3 MHz) and one low-frequency (650 KHz) piezoelectric crystal are each mounted 180° apart on a head that is rotated at 360 rpm by an ac synchronous motor. A fluxgate magnetometer is attached to the rotating head and when keyed to the crystal provides azimuthal orientation of the crystals. If operation is in borehole casing or in a confused magnetic flux field, a switch, also attached to the rotating head, provides a once per revolution orientation mark.

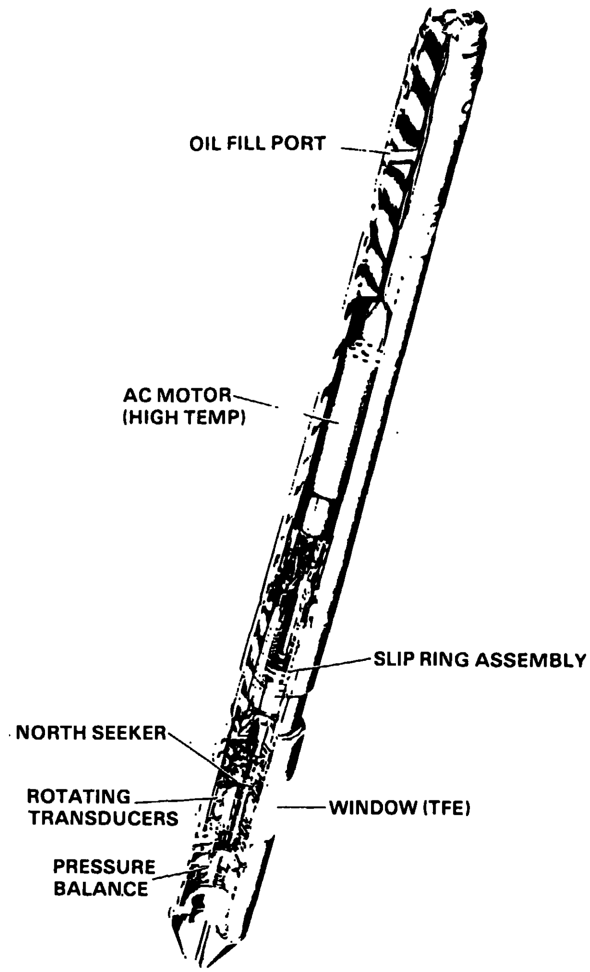

Figure 1. Downhole acoustic subassembly.

A thin TFE Teflon acoustic window separates the borehole fluids from the rotating crystal assembly. This assembly is mounted in an oil-filled cavity where the internal pressure is maintained to within 5 psi of the fluid pressure in the borehole using a pressure balance system. The TFE Teflon window is designed to "float" in the sealing mechanism to allow for thermal expansion when subjected to the high-temperature borehole fluids.

DOWNHOLE ELECTRONICS

The downhole electronic system is designed around an Intel 8085A-2 military-version microprocessor which is utilized to control data acquisition, processing, and transmission (Fig. 2). The microprocessor clock frequency is 10 MHz. The onboard instruction set is stored on EPROM, but RAM is available in the system to run programs sent via wireline using PCM format from the surface.

Raw data are fed to the CPU using two analog-to-digital converters. Acoustic data from the crystals are bandpass amplified and input to a TRW 700 8-bit video A/D converter and stored in a fast RAM (Fig. 3). The data are then entered into the CPU from the RAM. The sampling rate of the TRW A/D is 10 MHz and the same 10-MHz clock is used to step through 2048 addresses in the fast RAM. Therefore, the sampling window for the acoustic data is 204.8 μ s. Data from the fluxgate magnetometer, X, Y, and Z inclinometers, fire voltage, and two dewar temperatures are multiplexed and feed to an Analog Devices 12-bit CMOS A/D converter with a sampling rate of 96 KHz (Fig. 4). The microprocessor controls the sample and hold circuitry as well as the multiplexer and A/D converter in order to read and process orientation, temperature, and fire voltage data at various intervals during one revolution or 128 crystal firings or shots.

Data is transmitted to the surface through a 64 Kb/s PCM link via 7-conductor wireline. The downhole processor controls a Harris 15531 PCM encoder/decoder that transmits two 24-bit PCM words per shot. Each 24-bit PCM word is composed of three 8-bit bytes. For each byte or segment of a byte the microprocessor assigns a reduced data value or process variable to be sent to the surface. Appending these three bytes form the 24-bit PCM words.

The downhole microprocessor and peripheral electronics initiate tool parameters, PCM data transmission format parameters, as well as gather and process data in five steps. These five steps are the motor start/system initialization sequence and four cycles of a 3-KHz clock that is wired to one of the interrupt ports on the 8085 CPU.

On power-up, the system allows the motor power to stabilize and then starts the motor. The processor checks for proper rotation of the motor. If the motor is not operating properly the power to the motor is cut and the start-up sequence is reinitiated until the motor starts. When the motor is operating properly, the processor selects the predetermined crystal transducer for firing, sets the attenuator in the acoustic amplifier circuit to a predetermined value, sets up fast RAM, initializes the PCM encoder with the proper format, and prepares the system to gather and process data.

During the next four clock cycles, the system fires the crystal, acquires, analyzes, and transmits data to the surface. The time of each cycle is the period of the 3-KHz clock (approximately 333 μ s).

To begin, the first clock cycle fires the crystal and waits approximately 35 μ s for the crystal to ring down. After the ringdown interval, the acoustic A/D converter is started and the processor is then halted to eliminate noise in the system. A hardwired interrupt restarts the CPU and the processing of acoustic data stored in the fast RAM data is begun. A PCM word is composed with 2 bits of orientation, attenuation value, 11 bits of travel time and an

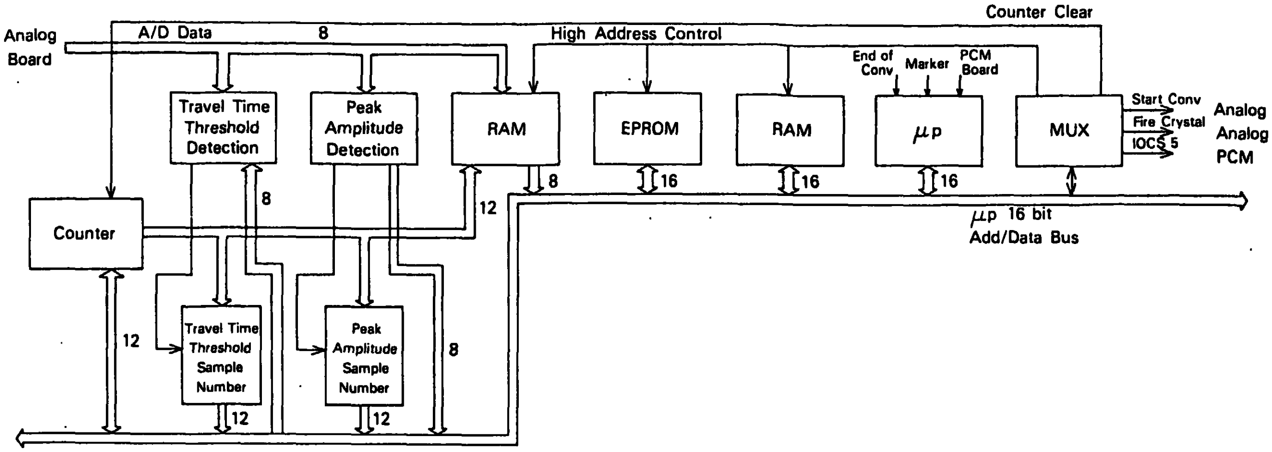

Figure 2. Block diagram of downhole microprocessor board.

8-bit peak amplitude value. The first PCM word is sent and the travel time and amplitude values are stored in memory for statistical analyses during subsequent operations.

In the second clock cycle the processor configures the system to measure the negative sense fluxgate sampler through the 12-bit A/D converter. A flux value is then composed with sign and stored away for filtering and analysis.

The third clock cycle is utilized for general system bookkeeping. Depending on the value of the shot counter, 0 to 127 for each revolution, the system is programmed to perform one of several different tasks. During this cycle, the second PCM word is composed and transmitted. The information in this second word is a function of the particular task being performed by the processor. The word could consist of inclinometer, temperature, or fire voltage values which are read from the 12-bit A/D converter or a short, medium or long time constant filtered flux value that is calculated throughout the revolution. One of these afore-mentioned values is appended with a calculated differential travel time value and the entire word is transmitted to the surface.

The fourth clock cycle measures the positive sensing fluxgate sampler. This positive source flux value is stored and filtered. The rotational position of the transducer is poled and compared with north orientation as well as a

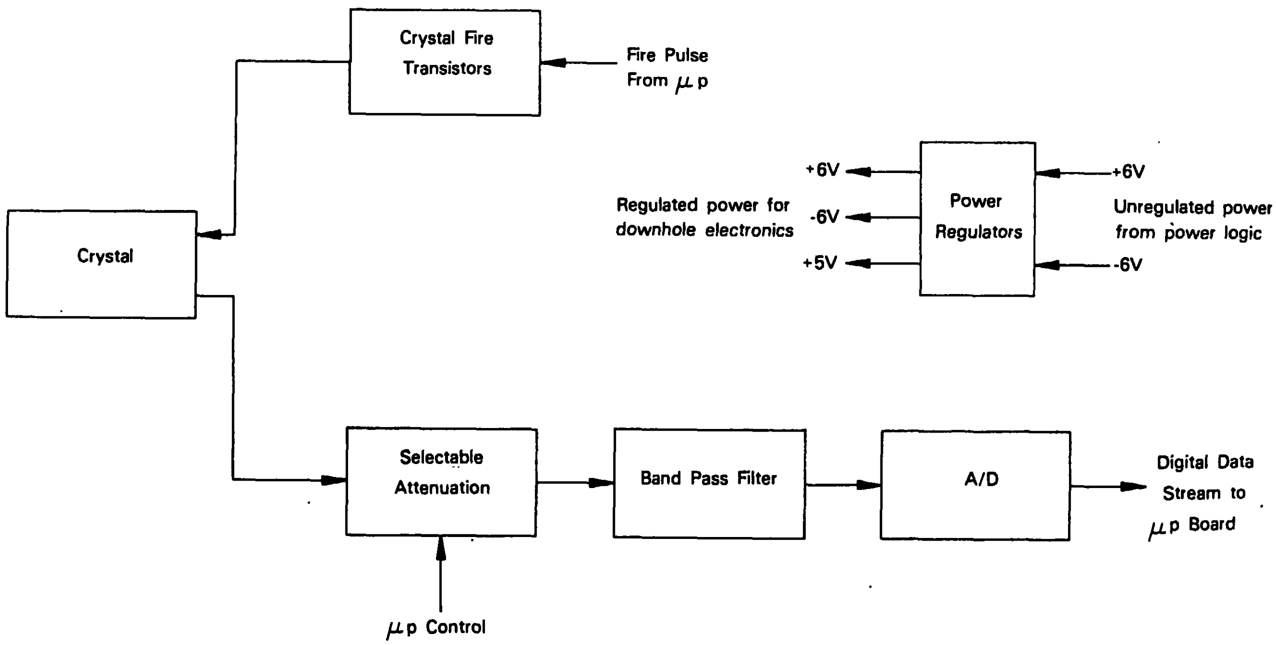

Figure 3. Block diagram of downhole analog acoustic board.

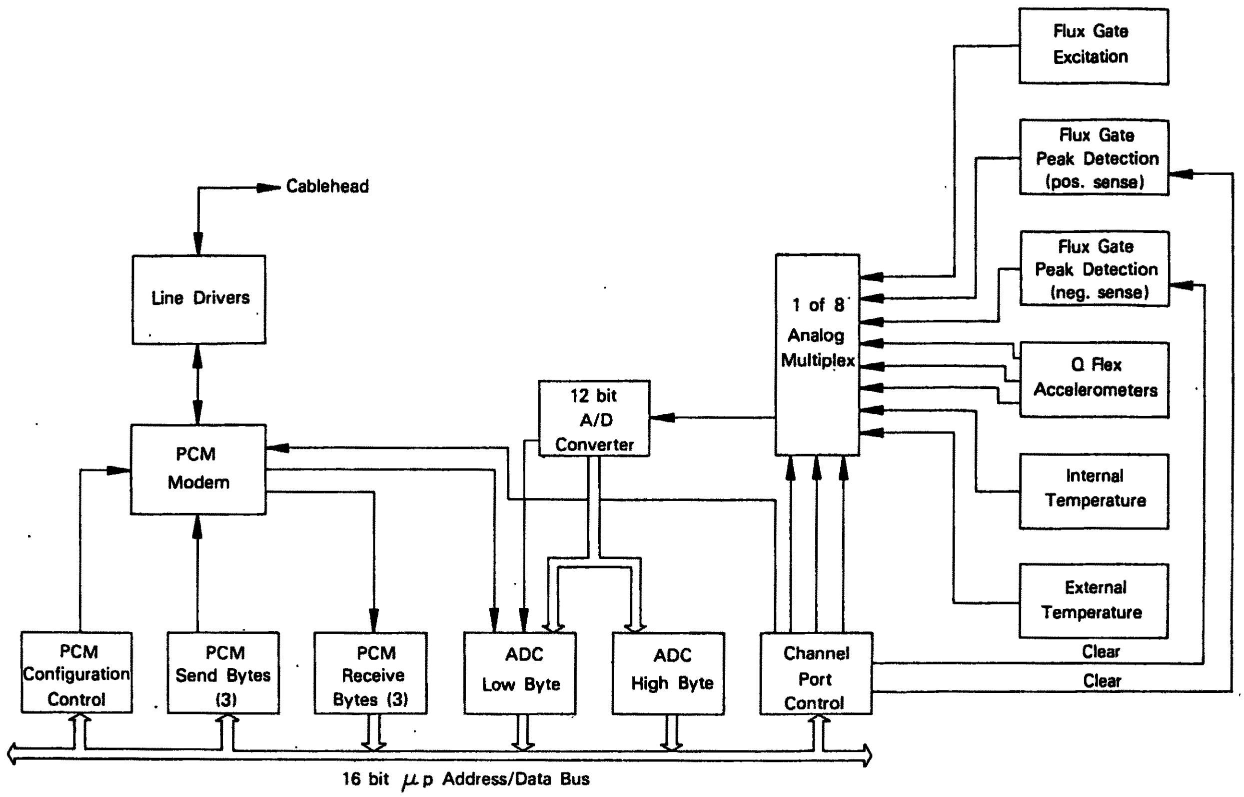

Figure 4. Block diagram of downhole PCM/analog board.

revolution marker. The peak value of the last shot is retrieved from memory and compared to percentage maximum and minimum values of the full scale input to the acoustic A/D converter, and the attenuation value is changed if necessary. The rotational position and attenuation value compose a segment of the first PCM word and the processor prepares the high byte of the first PCM word. At this time counters and latches are set to prepare for next shot. The CPU then loops to the first clock cycle and the four-step process is repeated.

The downhole electronics system is contained in a specialized dewar flask to protect the system from the harsh geothermal environment (Fig. 5). The internal temperature in the electronics compartment of the dewar is expected to be less than 100°C after 6 h of operation with the flask outer temperature at 275°C for 5 h of residence time. This allows for 1-h insertion and 1-h removal time. After 7 h of operation, the internal temperature is less than 120°C. The electronics system dissipates a 15-W heat source and includes 21 in. of heat sink in the form of Cerrobend. A specialized electric package housed within the dewar flask includes a 16-pin bayonet connector mounted on each end to provide a protected direct connection between the electronics inside the dewar and the sensors mounted below the dewar (Fig. 6).

UPHOLE CONTROL UNIT

The uphole control unit is constructed around the Siemens PMS-T 85D Microprocessor System (Intel 8085 CPU). This subsystem provides the user interface, controls the real-time outputs, and records the collected data on tape (Fig. 7).

The uphole control unit provides the interface between the tool and the user. To initiate and control tool operation, commands are entered at the system terminal. The format of the real-time outputs can be changed at any time. Once-per-revolution parameters displayed on the system terminal provide insight into the condition and operation of the tool.

Upon arrival at the surface, the data stream is decoded, and the serial data are stripped off and placed in a parameter buffer. Travel time and peak amplitude values are separated and written to buffers. Date/time and logging rate values are input from external sources and included in the parameter buffer.

Data collected by the tool are displayed on a color monitor. A hardcopy may be generated by the gray scale recorder. Data are mapped to intensities via a user-selected lookup table. Using mark and magnetic north information, data

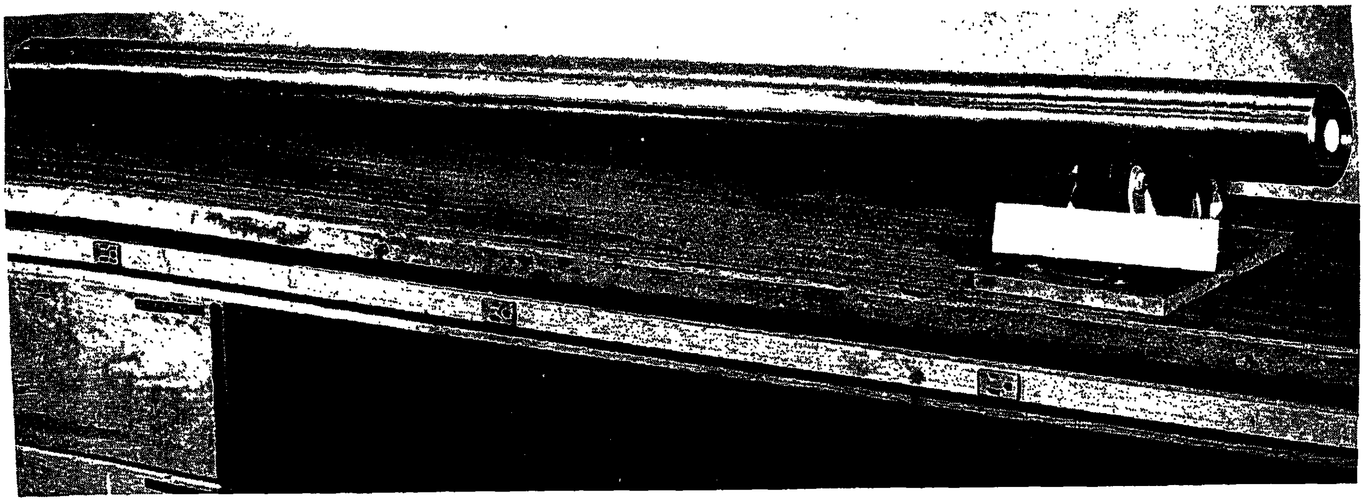

Figure 5. Dewar used for thermal protection system.

from a revolution are rotated to position the shot representing north as the first pixel in a raster scan line. Values from successive revolutions are inserted into the graphics controller such that the output of the color monitor will illustrate moving along the borehole.

Data are written to a 1/4-in. streaming tape on a revolution (mark-to-mark) basis. When all data from a revolution are present, the three buffers are written to tape as three records. A second set of buffers are present to allow concurrent I/O operations.

Real-time outputs may not provide sufficient information for an application. Off-line processing allows the user to manipulate collected data to meet specific needs.

The 1/4-in. tape provides a medium for transferring data to a minicomputer for further analysis. A first step may be to organize the data into a standard format before any additional processing. Operations involved may include (1) data calibration, (2) rotating data using north information, (3) evaluation of borehole deviation, and (4) correction for tool not centered in borehole. Once initial processing has occurred, the data collection may be broken up into segments and placed in directories representing ranges of depths.

At this point, mission specific software may be applied. Such algorithms may include image enhancement, statistical analysis, pattern recognition, etc.

CONCLUSION

The advantages of the microprocessor system approach as implemented in the downhole system are threefold. The microprocessor-based digital system with the duplex PCM telemetry link allow for modifying various logging parameters, i.e., transducer frequency, amplifier gains, and number of shots per revolution by simply reprogramming the system "on the fly" from the surface. This eliminates time consuming tool retrieval, disassembly, rewiring, and assembly. Secondly, the digital-based system lends itself to a "stop and listen" approach to decrease noise. Also, the crystal firings can be synchronized to nontransition times in the high-voltage motor-driver waveform to reduce crosstalk and enhance the acoustic signal. Recent field tests of the prototype BAT system in the Fenton Hill Hot Dry Rock geothermal boreholes have confirmed the increased resolution and much improved signal-to-noise ratio. The microprocessor-based system with the rotation of the acoustic head at 360 rpm has permitted increased logging speeds of 25 ft/min. In fact, scanning rates of up to 100 ft/min may be used to find damaged casing, washouts, and general borehole conditions which

Figure 6. Dewar showing bayonet connector.

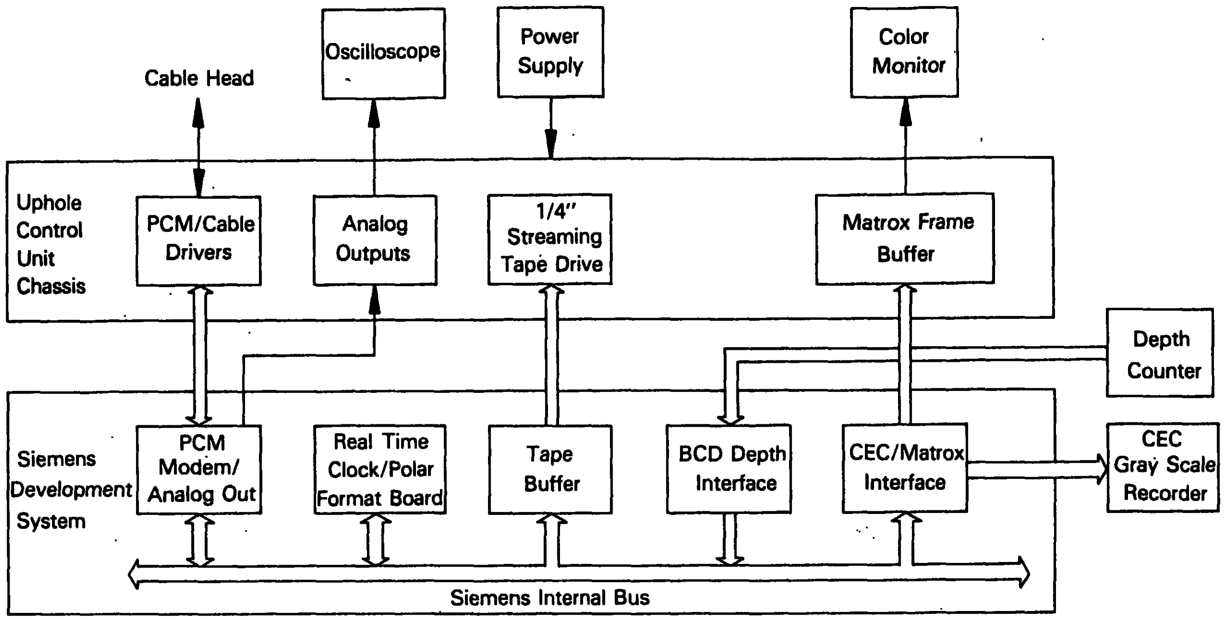

Figure 7. Uphole control unit block diagram.

maximizes the utilization of precious downhole logging times.

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