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DATA ACQUISITION, ANALYSIS, AND CONTROL WHILE DRILLING WITH HORIZONTAL WATER JET DRILLING SYSTEMS

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ABSTRACT

Two different horizontal water jet drilling systems have been developed and extensively field tested. The first, the Ultrashort Radius Radial System (URRS) is built around 32 mm (1-1/4 inch) coiled tubing and provides multiple 30 to 60 m (100 to 200 foot) radials from a vertical borehole. Accuracy is ± 2 to 3° in vertical trajectory.

The second system, the Remotely Piloted System, uses 114 mm (4-1/2 inch) conventional flush joint tubing and is designed to drill for many kilometers (miles) with high three dimensional accuracy. Both systems incorporate Control While Drilling of the radial and provide real-time acquisition and display of drill performance with derived formation properties.

I. INTRODUCTION

About ten years ago, Petrolphysics and its partner Bechtel began the development of the Ultrashort Radius Radial System. That water jet drilling system is described in several previous publications, among them References 1-8. Two water jet drilling systems have been developed for different applications and trajectories.

References and figures at end of paper.

The first system, the Ultrashort Radius Radial System (URRS), is an extended completion or recompletion system built around 32 mm (1-1/4 inch) coiled tubing and designed to provide 30 to 60 m (100 to 200 foot) radials on one or several levels within a single vertical well. Integrated with the water jet drilling technologies in the URRS are real-time data acquisition, data analysis and interpretation, and open/closed loop control while drilling systems. This platform provides a powerful information system interface through which a multitude of operational data is channeled to a single operator for real-time qualitative and quantitative analyses of the drilling process. Combined with a time-window display and database of past drilling information, the system facilitates immediate well management decisions and solutions to difficult problems as related to the drilling process. (Figures 1 and 2.)

The second system, the Remotely Piloted System (RPS), is also designed to provide multiple radials but at trajectories of up to several miles in length. The RPS is built around 114 mm (4-1/2 inch) screwed flush joint tubing and incorporates a removeable inner 63.5 mm (2-1/2 inch) Drilling and Control Module (DCM) which may be removed and replaced by coiled tubing or sucker rods without tripping the outer 114 mm (4-1/2 inch) drillstring.

II. SYSTEMS DEFINITION

A. Ultrashort Radius Radial System (URRS)

The particular properties of the URRS include the following capabilities. Specific references to each technology are indicated.

1. Make a vertical to horizontal turn on a one-foot radius.[1,2,7]
2. Provide multiple radials from a single vertical well.[1,2,7]
3. Water jet drilling of borehole from a diameter of many millimeters (a few inches) to more than one-third meter (a foot) in a wide variety of rocks at high backpressure and depth.[3]
4. Provide a variety of horizontal completions including horizontal gravel packing, Flexible Sand Barrier (flexible permeable casing), and electrolytic cutting and perforating.[6,7]
5. Flexible three dimensional positional logging with initial directional placement accurate to $\pm 0.5^{o}$.
6. Data acquisition and analysis to provide both real-time indication of operating systems effectiveness and downhole data on the formation.

To make this system more effective, it was obvious that real-time Control While Drilling (CWD) capability was required for the URRS. This was a long expensive developmental effort with many failures and trials along the way. Many systems were evaluated. The CWD system which was successfully carried to commercial fruition incorporates four side jets (thrusters) which are controlled by individual electric piloted, pressure switched valves shown in Figure 4. The signals for valve operation evolve from an on-board, real-time roll and pitch (inclination) sensitive switch. All these components function within the 32 mm (1-1/4 inch) coiled tubing and are immersed in a 69 MPa (10,000 psi) pressure environment. Electric power is provided by wireline from the surface which is connected through the radial to the electronics. With the present URRS, the radial follows a preset trajectory. Future capability, which is well along in development, includes the ability to feed back real-time trajectory data to the operator at the surface via the wireline and to provide real-time trajectory Control While Drilling of the 32 mm (1-1/4 inch) radial tube.

B. Remotely Piloted System

The Remotely Piloted System (RPS) incorporates several objectives and properties different from the URRS:

1. Achieve horizontal trajectories of many kilometers (several miles).
2. Incorporate real-time, remotely piloted control of drillstring trajectory.
3. Permit rapid removal and replacement of a downhole Drilling and Control Module (DCM) without tripping the drillstring.
4. Incorporate a high data rate, wireline data link between a downhole Drilling and Control Module and an uphole operator.
5. Adapt conventional drilling fluid rheology and slurry techniques to transport the cuttings for the required length of trajectory and/or frac the cuttings into the formation.
6. Provide Case While Drilling and a variety of other completions.
7. Ultimately achieve a drilling system which can core and can sense and follow a pre-selected geological structure.

III. CONTROL WHILE DRILLING EQUIPMENT AND PROCESSES

A. URRS

A drillstring can move in four directions (degrees of freedom in movement). In the URRS, three of these movement directions (degrees of freedom) are controlled while drilling.

The first direction of motion, penetration (axial), is controlled by a sealed piston (Motion Controller) attached to the 32 mm (1-1/4 inch) drillstring. This piston, which is analogous to a fluid shock absorber consists of a set of seals and fluid drain orifices. There are no moving parts. The rate of penetration of the drill is preset by the orifice size. This unit is shown in Figure 3.

Inclination (up/down) is the second direction of motion. It is determined in real-time by an electromechanical inclinometer contained within the 32 mm (1-1/4 inch) drill head. This device, which also compensates for roll (the third direction of motion), switches the power among a set of small locking solenoids. The actual up/down control mechanism consists of four small side thruster jets placed at 90 degrees to each other on the drill head. The thruster jets are valved by flow actuated valves, powered by the high pressure 69 MPa (10,000 psi) water drilling fluid. These valves are either held open by the small locking solenoids or allowed to close as required to correct variations in the trajectory inclination. Azimuth (right/left) movement, the fourth direction of motion, is not directly controlled. The CWD concept is shown in Figures 3 and 4.

B. Remotely Piloted System

1. Long Horizontal Trajectories

The principal limitation to extended reach drilling using hydraulic propulsion is the frictional interaction of the drillstring with the formation. To handle the internal pressure drops for trajectories of many miles and the 69 MPa (10,000 psi) drilling fluid, a 114 mm (4-1/2 inch) flush joint drillstring was selected as a design basis. From experience with the smaller 32 mm (1-1/4 inch) URRS, it was clear that a non-rotating drillstring could not achieve a low enough coefficient of friction for multi-mile horizontal trajectories. Therefore, a detailed full scale laboratory test program was made of rotating drillstring friction as a function of the ratio of rotational velocity/translational velocity. The following variables were also examined in that test program: Formation constituency and consolidation, fluid saturation, drilling fluid additives and overburden pressure. The conclusions of the work indicated that for the desired rates of penetration (ROP) of .3-3 m/min (1 to 10 ft/min) the desired rate of rotation was in the range 5-30 rpm with an average of 15 rpm. As an example, with a typical unconsolidated, coarse grained sample of 1.3-1.9 g/cc (80-120 lb/f^3) having 4% water saturation and utilizing water as drilling fluid, the measured coefficient of friction was .1 to .3.

2. Real-time Remotely Piloted Control

With a fluid jet drilling system, it is possible to achieve Control While Drilling (CWD) by two methods. The first control system uses valved side thruster jets, as with the side reaction jets used in the URRS. It is described in Reference 8. For a 114 mm (4-1/2 inch) drillstring, the available force with the side thruster technology is insufficient to adequately deviate the larger, heavier string. Therefore, the second method was developed.

The second CWD method makes use of a multiple, forward directed jet system within a 114 mm (4-1/2 inch) rotating drillstring. Each forward jet is at a slightly different obliquity. Internal electric powered, servo controlled, valving of the high pressure 69 MPa (10,000 psi) drilling fluid distributes the drilling fluid to the desired nozzle for cutting. The ability to control flow to the separate nozzles when used in conjunction with an on-board gravity vector sensor allows real-time multidirectional control. A sketch of the Drilling and Control Module (the forward portion of the drill head) is shown in Figures 5 and 6.

The remotely piloted capability is provided on the surface using a keyboard input to a PC type computer, a wireline link downhole and a 63.5 mm (2-1/2 inch) Drilling and Control Module placed within and at the nose of the 114 mm (4-1/2 inch) drillstring.

3. Removeable Drilling and Control Module

To provide a long reach capability without requiring excessive rig or trip time for downhole equipment replacement, a capability to trip the jet drilling system and the downhole electronic control components without tripping the entire drillstring was developed. The outer 114 mm (4-1/2 inch) pressure bearing element of the drillstring thus remains in the drilled borehole section and positively maintains hole integrity while the internal electronic-mechanical equipment (DCM) is changed. This system is shown schematically in Figures 5 and 6. As indicated, the drillstring is really two concentric strings. The outer 114 mm (4-1/2 inch) string bears the pressure, the formation interaction forces and abrasion. The inner 63.5 mm (2-1/2 inch) DCM is removeable from within the larger drillstring. The DCM contains the valving for the drilling fluid, the guidance and control components (stable platform) and power supply buffer components. Although portions of the DCM can withstand external pressure (canned electronic systems), it serves only as a conduit and valving system to focus and direct the drilling fluid for drilling and CWD.

The DCM is held against a lip seal within the larger drillstring, as shown schematically in Figure 5 by the drilling fluid hydraulic pressure. The DCM may be retrieved or replaced by wireline, by sucker rods or by coil tubing. During removal or tripping, positive water flow is maintained down the 114 mm (4-1/2 inch) drillstring to avoid draw-in and contamination by formation or cuttings. This procedure was used in the initial field tests.

4. Wireline Data Link

Many methods of real-time data transmission were evaluated and/or tested: mud pulsing, seismic, earth current, rf, ultrasound in both the water column and tubing, and wireline systems. Based upon the trials of each, wireline technology was concluded to be the best way to get a combination of a high data rate, reliability and a good signal-to-noise ratio for trajectories of several miles.

Three wireline methods were evaluated: (a) a downhole or uphole spooled system feeding out wire (analogous to the TOW Missile System), (b) a connector-joined system with a connector for each pipe joint or (c) a screwed connector system containing wireline. All have problems.

IV. ULTRASHORT RADIUS RADIAL SYSTEM (URRS) DATA ACQUISITION AND ANALYSIS

The URRS data acquisition system can be divided into several functional entities. (A schematic is shown in Figure 2.) These entities are: Signal waveform transporters; signal conditioning; digital converters; mathematical regression equations, database integration and interpretation techniques; information system interface; user input and control messages; data storage, replay and hard copy output.

The signal waveform transporters or "data nervous systems" are comprised of a number of transducers and sensors. The transducers monitor important environmental system parameters and provide real-time analog signals. The incoming signals are conditioned to eliminate system noise and scaled to meet A/D input span specifications. Downhole signals can be channeled through a microprocessor and analog multiplexed or frequency shift keyed to the surface. Additional enhancements include power, data signals and communications transported concurrently over a single wireline.

The conditioned signals are processed by an analog/digital converter at rates up to 5000 Hz and up to 16 channels of simultaneous data. Acquired data rate is adjustable depending on the desired interpretation of the data. Rate of penetration is currently acquired through optical encoders and a four axis quadrature counter. Distances can be preset for key event diagnostics. All incoming data is imprinted with real-time clock information for post analysis.

A computer processes the large amount of data for immediate interpretation. Computer-simulated filters buffer the now digital data to extract specific data for analysis. Developed mathematical models and algorithms organize the data into easily understandable and relatable parameters. The data is the displayed to the operator on a single console using overlay techniques. Background waveforms are scrolled across the screen to give an immediate account of the interpreted data as well as an historical account of past data. Foreground information displays scaled windows and modeled information such as effective nozzle areas and system runtime information. Warning flags are implemented for abnormal operations to prevent system failure.

The operator can control various parameters which effect system interpretations as well as control data display. Post analysis of the data includes interfaces with databases of past drilling operations for establishing models of the present drilling assignment. The data is permanently stored for post analysis of run history including playback and hard copy.

The data acquisition system is used for all aspects of the Ultrashort Radius Radial System as well as during runtime. Logging tools and completions systems are integrated as part of the system analysis.

V. RESULTS

A. Ultrashort Radius Radial System

In field applications in a variety of formations and depths the Ultrashort Radius Radial System with Control While Drilling demonstrates a $\pm$ 2 to 3° vertical deviation. (This results in about a 1.1 to 1.5 m (3.5 to 5 foot) vertical deviation per typical 30 m (100 foot) of horizontal trajectory). The system is run from a control truck by a single operator. There is no one on the rig floor during drilling operations which normally take only a few minutes to place a 30 to 60 m (100 to 200 foot) radial in an unconsolidated formation.

The data acquisition and analysis system provides the operator, the tool pusher, and the company man immediate and continuing real-time indication of system performance. As well, a correlated catalog of formation parameters and system data is being constructed based upon field results in sandstone, carbonate, and unconsolidated formations. This catalog has been very useful in interpreting the formations and optimization of subsequent radial placement.

B. Remotely Piloted System

The initial phase of the Remotely Piloted System field trials was accomplished over a one year period wherein a special top drive rig was constructed embodying hydraulic drilling and drillstring propulsion. This prototype field work was done in a well cored geological structure in the U.S. which included unconsolidated material, granite boulders or cobbles, clay, silt and mixtures thereof.

Subsequent to this successful field drilling trial of the first generation unit, a second generation system was designed, built, and tested in the laboratory. The unit incorporated real-time, joystick Control While Drilling coupled with a Drilling and Control Module which could be removed without tripping the drillstring.

VI. CONCLUSIONS

A. Ultrashort Radius Radial System

The URRS Control While Drilling has demonstrated the capability in the field to control the drillstring trajectory to within 1.1 to 1.5 vertical meter (3 to 5 vertical feet) per 3° horizontal (100 horizontal feet) of trajectory. This corresponds to a $\pm$3° error for radial placement. Rate of penetration can be controlled from 6 m/min (20 ft/min) down to 0.15 m/min (0.5 ft/min). Horizontal trajectory is not controlled, but post placement positional logging measurements suggest a correlation of azimuth or yaw trajectory with inclination or pitch trajectory.

The data acquisition and analysis system has proven to be a powerful and highly useful tool for controlling drilling, failure analysis, and real-time geological input. The software is easy to use and training is rapid. With the growing catalog of results being accumulated into a database, the foundation for an Expert System is being created. This will help optimize the control of radial trajectory in terms of the actual geology.

B. Remotely Piloted System (RPS)

The 114 mm (4-1/2 inch) first generation system has demonstrated the capability to horizontally drill a variety of formations in the field. Field results are not available with the second generation of the RPS.

The RPS control system is designed to drill as a true remotely piloted system. The operator has the opportunity to achieve a highly accurate, controlled trajectory of the 114 mm (4-1/2 inch) drillstring for many miles. With an on-board guidance system, potential error boundaries are small. The Drilling and Control Module permits replacement of the bit and electronics without tripping the drillstring and offers the opportunities both for real-time geological data acquisition and for removal to permit coring.

VIII. ACKNOWLEDGMENTS

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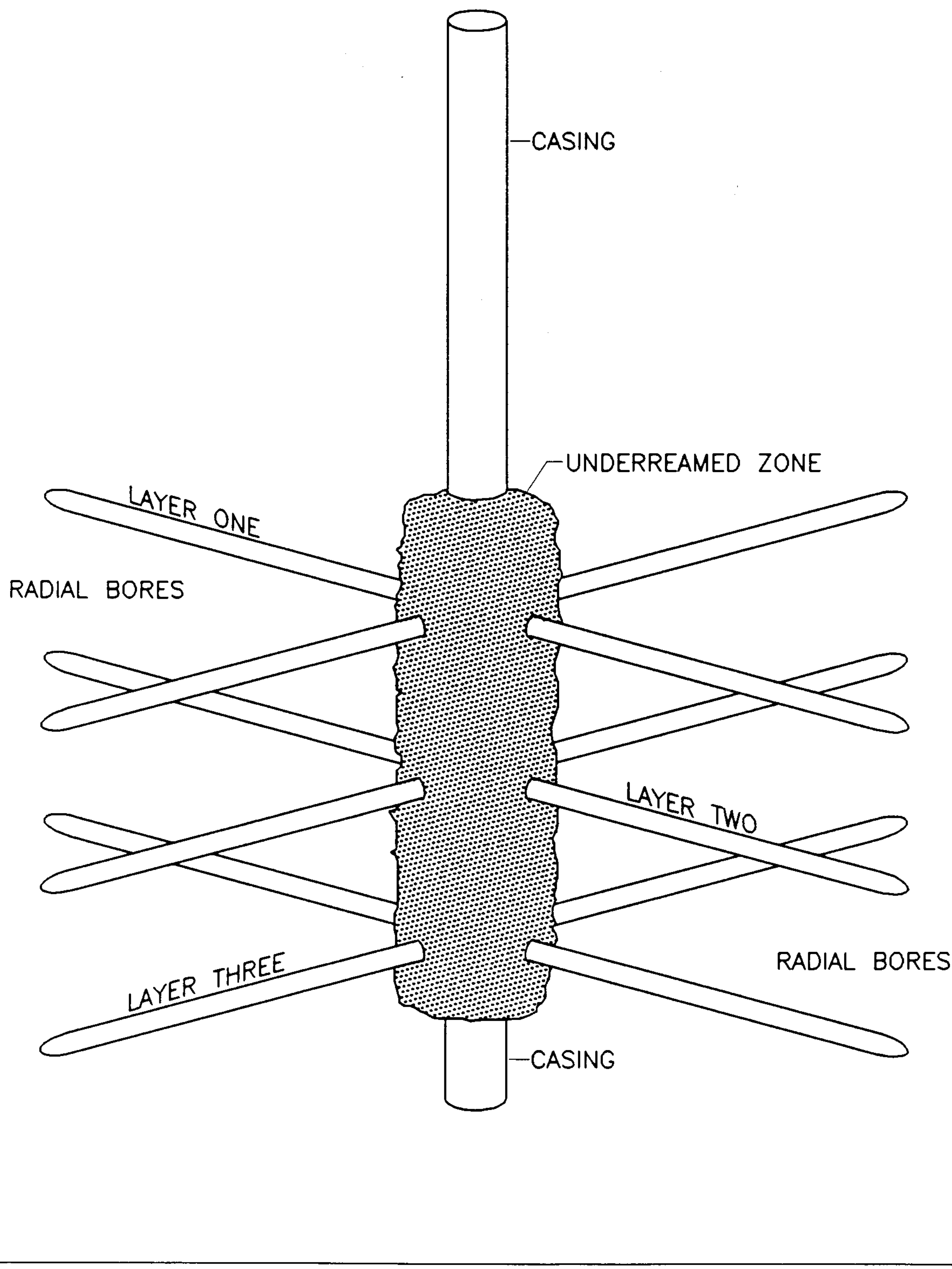
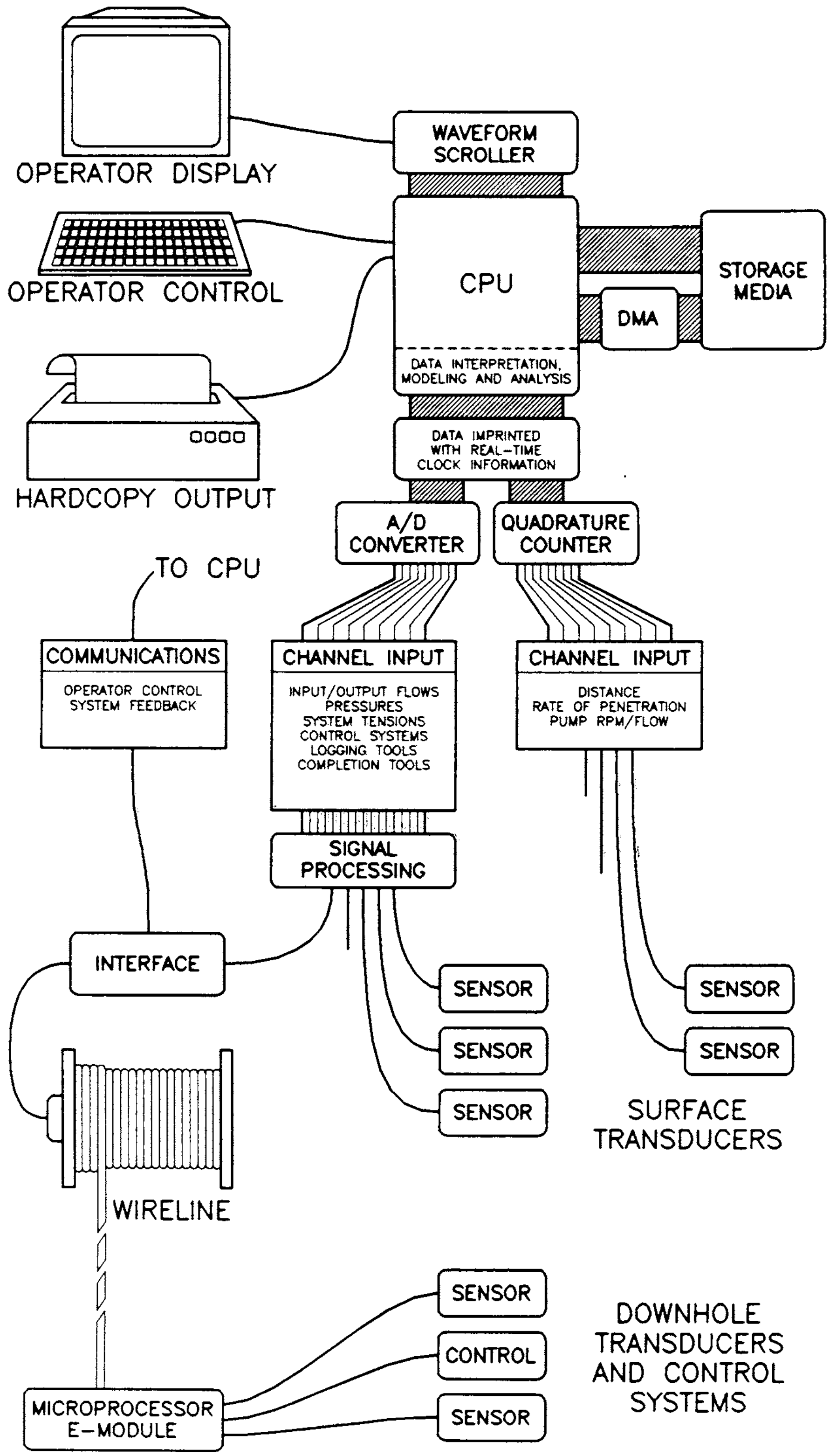
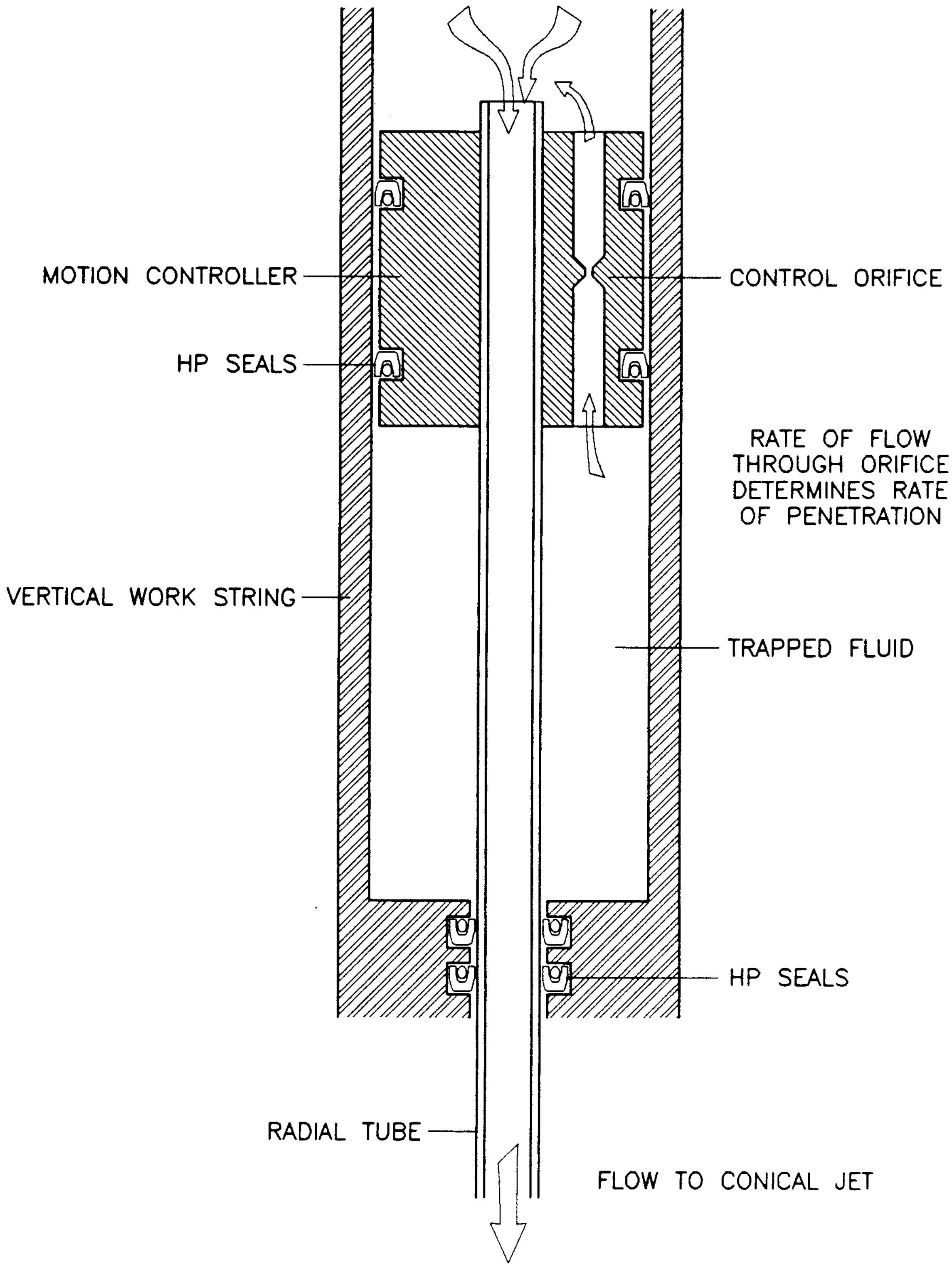


MULTIPLE RADIAL COMPLETIONS
FIGURE 1

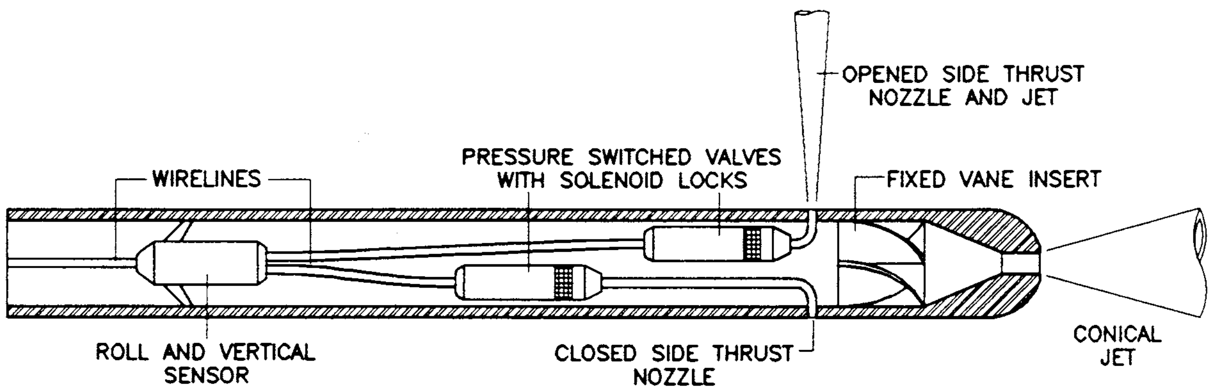


DATA ACQUISITION SYSTEMS SCHEMATIC

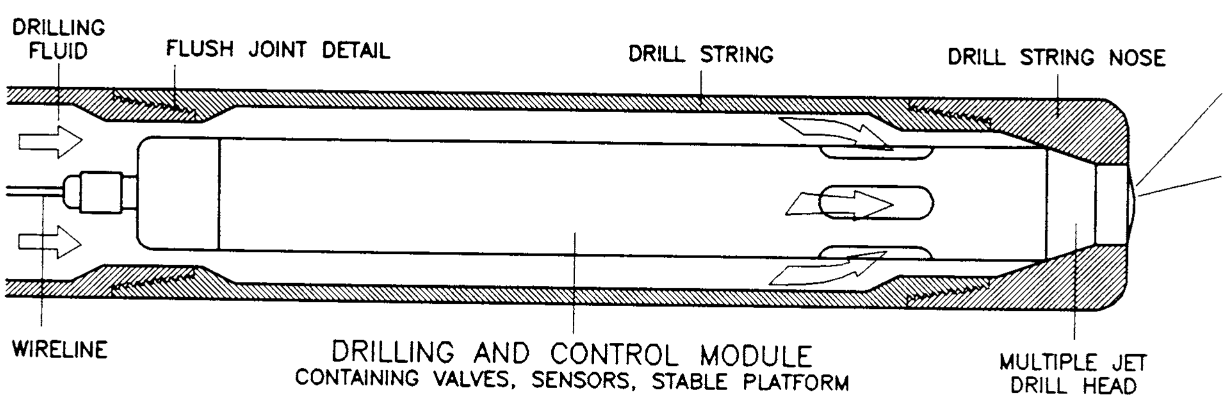
FIGURE 2



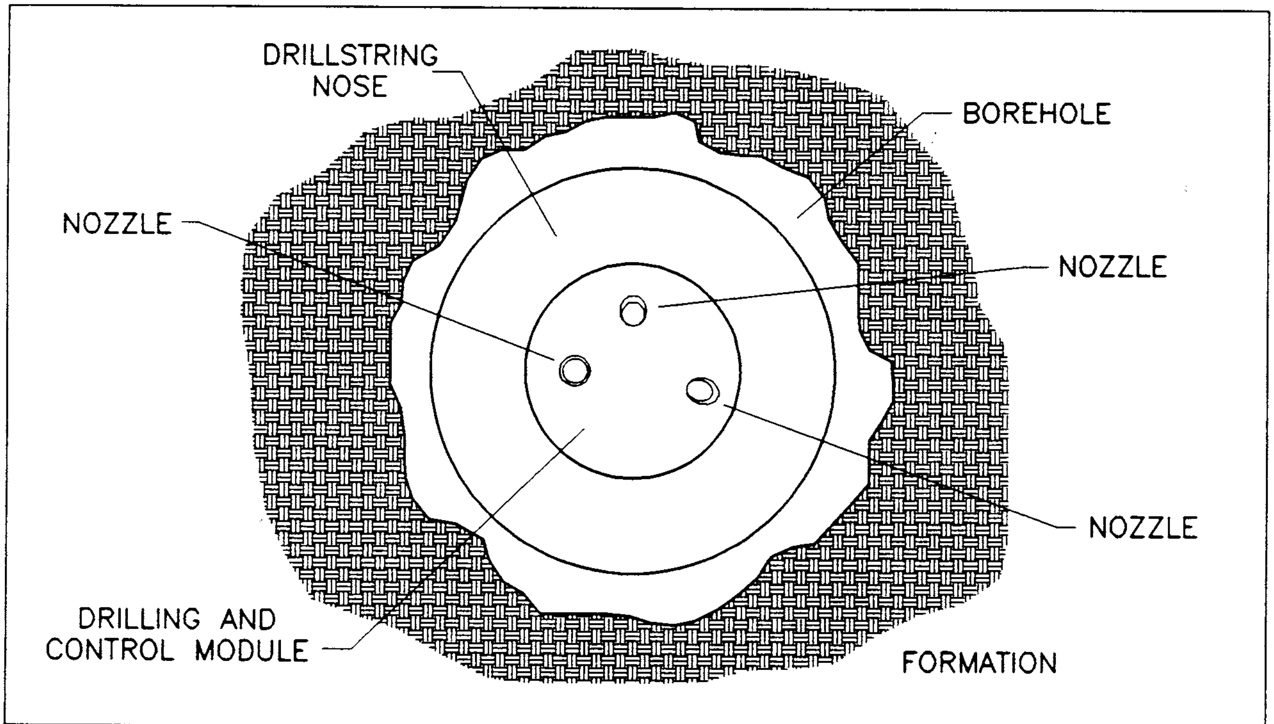
RATE OF PENETRATION CONTROL WHILE DRILLING
FIGURE 3



VERTICAL DEVIATION CONTROL WHILE DRILLING
FIGURE 4



REMOVEABLE DRILLING AND CONTROL MODULE
FIGURE 5



DRILLING AND CONTROL MODULE IN FORMATION
FIGURE 6