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**MUD PULSE LOGGING WHILE DRILLING
TELEMETRY SYSTEM—DESIGN,
DEVELOPMENT, AND DEMONSTRATIONS**

By

Teleco Oilfield Services, Inc.

Prepared for DOE
Under Contract No. ET-76-C-03-1817

Date Published—July 1978

Bartlesville Energy Research Center
U.S. Department of Energy
Bartlesville, Oklahoma

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FOREWORD

This report covers work performed under DOE Contract No. ET-76-C-03-1817 (formerly EY-76-C-02-4046).

The contract was approved by the Division of Oil, Gas, Shale and InSitu Technology. Mr. Hugh D. Guthrie, Director, and was funded by the Branch of Drilling and Offshore Technology. Mr. Don Guier, Branch Chief. The work is monitored by the Bartlesville Energy Research Center (BERC). Mr. John S. Ball, Director. BERC also furnishes the Technical Project Officers.

The contract resulted from an unsolicited proposal from Teleco, Inc., dated February 24, 1976, for development and demonstration of its mud pulse telemetry system for directional drilling. The contract covers design improvements, field testing with three improved prototype tools, building eight new tools and a 12 month Pilot Service Demonstration. It is a cost-sharing venture between Teleco and DOE with significant participation by six oil companies: Amoco International, Chevron Oil Field Research, Continental, Exxon U.S.A., Placid and Shell.

DOE's objective in funding the contract was to accelerate the commercial availability of a dependable telemetry system that will prove useful to the petroleum industry by reducing cost and drilling time. Such accomplishments are in line with the DOE goal to increase domestic production and achieve energy independence. The results obtained have already been highly successful and shows that the concept of cost-sharing with industrial companies to stimulate research and development can be very beneficial to both the public and the industry-at-large.

The Pilot Service Demonstrations will continue through August 1978. The monthly and quarterly reports submitted by the contractor are on open file at Bartlesville Energy Research Center.

C. Ray Williams
Technical Project Officer
Bartlesville Energy Research Center

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This paper (except for the Addendum) was presented at the 1978 Drilling Technology Conference of the International Association of Drilling Contractors March 7-9, 1978, Houston, TX.

ABSTRACT

Mud pulse telemetry is a method of transmitting information from the vicinity of the drill bit to the surface drilling platform while drilling. Information can be conveyed through a flowing column of drilling mud by the presence or absence of pressure pulses arranged in a binary code. Pressure in the flowing mud column is periodically modulated at a point downhole by mechanical means, and the resulting periodic pressure pulses appearing at the surface end of the mud column are detected by a pressure transducer conveniently located in the standpipe.

Although the concept of mud-pulse telemetry is not new, only recently have sophisticated systems embodying mud-powered turbine generators and solid-state electronics been developed to the point of being able to withstand the hostile downhole environment. After ten years of active technology development and over \$10 million of R&D expenditures, Teleco has demonstrated through field tests carried out in the Gulf of Mexico during 1977, that equipment reliability necessary for commercial operation is essentially at hand.

Three generations of prototype systems were tested under actual drilling conditions during 1968 through 1977. Over 2,700 hours of bottomhole use were logged. Using eight new production systems, Teleco began a Pilot Service Demonstration in August 1977, under a contract with the U. S. Department of Energy and six major oil companies. Each system consisting of a sensor assembly and mud pulse telemetry transmitter, measures borehole azimuth, inclination, and tool facing. Accurate directional measurements have been provided from kick-off through to target depth with minimum interruption to the drilling operation. Tool face information has been used to successfully kick-off directional wells using both mud motor and jet deflection techniques. Equipment reliability, as indicated by recent test runs of 254 and 272 hours of drilling with two separate systems, without failure, is approaching the level needed for commercial service.

INTRODUCTION

Teleco was incorporated in 1972 as a joint venture of Raymond Precision Industries Inc., and Societe Nationale Elf Aquitaine (Production) and since then has focused its activities on the commercialization of a reliable mud pulse telemetry system. Field test results obtained in 1973 correlated closely with mathematical model predictions clearly establishing the practicality of the communications link from depths exceeding 17,000 feet. From that point on, emphasis has been placed on the task of improving equipment reliability.

In August of 1976, Teleco began a program for the final development and demonstration of its borehole telemetry system. In parallel with the continued testing of three existing prototypes, eight new systems (transmitters and directional drilling sensors) have been manufactured. Under a program jointly funded by the Branch of Drilling and Offshore Technology of the U. S. Department of Energy (DOE), a consortium of six oil companies, and Teleco's owners, the new systems are being used to carry out a one year pilot service demonstration program in the Gulf of Mexico which began in August of 1977. After a disappointing start owing to the faulty manufacture of certain bonded elastomer parts, the results of the pilot service demonstration are proving to be extremely encouraging. Results of the first six months of the program are discussed in this paper.

HISTORY OF DEVELOPMENT

The Teleco mud pulse telemetry technology originates with two completely independent research and development projects.

One project began in the mid-1960's at the Research Center for Societe Nationale Elf Aquitaine (Production) located in Pau, France. Early work by SNEA included field testing of a telemetry link which utilized the drill string as a carrier for acoustic energy. Initial field tests were conducted using a downhole assembly made up of a battery power supply, a pulse generator simulating a group of sensors, and an acoustical generator. Initial tests conducted while air drilling at a depth of 6,000 feet were encouraging. The acoustical signal, in the 5 K HZ range, was attenuated only 20 db/1,000 meters. With the drill pipe and annulus filled with drilling mud however, attenuation was severe, exceeding 150 db/1,000 meters.

SNEA conducted further tests in 1969 using an acoustic signal generator with a much lower natural frequency. The lower frequency signal generator demanded greater power and therefore the battery power supply was replaced by a more sophisticated turbine electrical generator assembly. At this time, a sensor measuring borehole inclination was added to the downhole assembly. See Figure 1. Once again field testing revealed severe signal attenuation. Signal energy was dissipated in the mud and in the formation. The acoustic telemetry program was stopped at the end of 1969.

Although this research led to the abandonment of the acoustic telemetry technique by SNEA, the practicality of a downhole turbine generator was demonstrated, and severe effects of downhole vibration and shock were evaluated leading to the design of special purpose vibration isolators.

In parallel with this acoustic telemetry work, SNEA began to advance the development of its mud pulse telemetry technology. Two prototypes of a downhole measuring and transmitting tool called PIH were designed and built and successfully field tested during 1969-1971.

The PIH system as shown in Figure 2 consisted of a transmitter, an electrical power supply (mud driven turbine generator), and sensors to measure borehole inclination. Two complete prototype systems were tested in France during 1969-1971. Over 800 hours of bottomhole test time were recorded. Significant achievements included transmissions from a depth of 11,250 feet and excellent correlation of inclination readings with Totco measurements.

During 1970-1972 an improved telemetry system called TEFOR was designed and tested in the field. The TEFOR system measured borehole inclination, azimuth, tool facing and turbine drill rpm. Two prototype TEFOR systems were tested in France and offshore in the Gulf of Mexico accumulating over 500 hours bottomhole test time during the course of 22 bit runs. The equipment functioned for periods ranging from 15 to 102 hours before failure.

The other project which contributed significantly to Teleco's mud pulse telemetry technology was carried out by a small group of engineers at Raymond Engineering Inc. in Middletown, Connecticut. Beginning in 1969 investigations concentrated on two promising

FIGURE 1—Schematic SNEA acoustic telemetry system.

FIGURE 2—PIH System.

telemetry techniques: acoustic telemetry and mud pulse telemetry.

Acoustic telemetry, a term generally reserved for the frequency domain of 500 hz and greater, was evaluated analytically and by use of a variable frequency vibrator which was acoustically coupled to a string of steel pipe. Although this technique was not evaluated in drilling wells, acoustic attenuation measurements made with drill pipe laid out on the ground (and immersed in mud) were enough to discourage the investigators.

The Raymond group designed and built a prototype mud pulse telemeter which was successfully tested at the Exxon Friendswood test well in 1971. This experimental tool was designed to generate mud pulses of various pulse widths and pulse repetition rates. Because the objective of this early work was not to develop a working tool but rather to verify theoretical transmission analysis, this experimental mud pulse telemeter was powered by batteries. This approach, of course, reduced development time and early development expenditures. Test results obtained with this experimental tool confirmed the theoretical analysis but equally important, the field experience made very clear the severity of the downhole drilling environment. Evidence such as parts badly worn by abrasive mud, leaky seals, shock and vibration effects all pointed to the need for a long term, deliberate product development if satisfactory equipment reliability was ever to be achieved.

The similarity between the two R&D projects is classic, considering that neither group was aware of the other's work prior to 1971. The two groups initially pursued battery powered devices. Acoustic telemetry was evaluated but each group chose mud pulse telemetry because of its potential for greater transmission reliability. Directional drilling measurements were chosen as a starting point for a commercial service.

In 1972 Raymond and SNEA pooled their technology in this field and incorporated Teleco. After testing the TEFOR systems, Teleco designed and fabricated three new prototype systems. Design modifications such as longer life seals, more rugged sensors and electronics assemblies, and a more reliable signal processing technique were evaluated in the Gulf of Mexico.

TELECO SYSTEM DESIGN

Principle of Mud Pulse Telemetry—Mud pulse telemetry is a method of transmitting information through a flowing column of drilling mud. In this process, the pressure in the flowing mud column at a point downhole is periodically modulated by mechanical means, and the resulting periodic pressure pulses appearing at the surface end of the mud column are detected by a pressure transducer conveniently located in the standpipe. Information can be conveyed by the presence or absence of pulses, or by the relative duration of pulses in a sequence.

Downhole Mud Pulse Generator—Pressure in the flowing mud column is varied downhole by placing a variable restriction in the path of the mud stream. As shown in Figure 3, this variable restriction consists of an orifice towards which is directed a poppet movable by hydraulic means. The poppet has two possible positions relative to the orifice. When the poppet is retracted away from the orifice, it has a negligible effect on the pressure drop in the mud as it flows through the orifice. But when the poppet is extended toward the orifice (it does not extend far enough to contact the orifice), it reduces the effective area of the orifice and thus increases the mud pressure drop across the orifice. Since for all practical purposes, the column of mud flows at a constant rate irrespective of poppet position, extending the poppet causes an increase in mud pressure, above the orifice. This pressure rise or so-called mud pulse travels to the surface inside the drill pipe at a speed of about 4,000 feet per second. The amplitude of the mud pulse as received at the surface (approximately 50 psi) is not substantially affected by mud density.

Data Encoding and Transmission—One ordinarily visualizes a measured

FIGURE 3—Downhole mud-pulse generator.

FIGURE 4—A method for representing a binary number by a series of mud-pressure pulses.

FIGURE 5—Alternate method for representing a binary number by a series of mud-pressure pulses.

parameter in terms of its value as a decimal number. But transmission of this decimal number along a noisy transmission path with the best possible resolution and least possible error requires that the decimal number be converted to its binary number equivalent and transmitted as such, and transmitting a binary number is precisely what the downhole mud pulse generator is intended for.

Consider as an example the decimal number 620, which might represent a downhole measurement of 62.0° hole inclination, or 62,000 pounds bit weight, or other downhole parameter of interest. The 10-bit binary equivalent of decimal 620 is 1001101100 obtained as follows:

$$(1 \times 512) + (0 \times 256) + (0 \times 128) + (1 \times 64) + (1 \times 32) \\ + (0 \times 16) + (1 \times 8) + (1 \times 4) + (0 \times 2) + (0 \times 1) = 620$$

The binary number 1001101100 is obviously directly portrayable as a series of pressure pulses. For example, after a marker pulse to signify the beginning of the number, each subsequent pulse could represent a binary one while the absence of a pulse would then represent a binary zero. This is shown in Figure 4. Another method could utilize a change in mud pressure level to represent a binary one and no change to represent a binary zero as shown in Figure 5. Several such schemes are possible, each of which has various advantages. The encoding method utilized by Teleco was chosen after careful evaluation of the various advantages in the light of the characteristics of the transmission path so as to minimize errors and maximize the data rate.

Data Detection—Binary (digital) data transmitted from downhole to the surface via the flowing mud column appears at the surface as a modulation on mud pressure level at the inlet to the drill pipe. For purposes of detection, a pressure transducer is installed in the standpipe upstream of the flexible hose. For the codes shown in Figures 4 and 5, the electrical output signal from this transducer would appear similar to the pressure

waveforms shown in those figures, except that it would contain additional variations caused by pressure pulses generated by the mud pump. In the detection process, the mud pump noise signal is eliminated by electronically filtering the signal from the pressure transducer. The binary ones and zeros contained in the filtered signal are then decoded by various logic and timing circuits and are converted back to the decimal equivalent number by conventional digital logic techniques. Finally, the decimal number is displayed by the surface detection equipment by means of a lighted decimal digit display device.

System Description—The Teleco telemetry system measures, transmits, and displays the following downhole parameters:

- Reference angle (tool facing); accuracy $\pm 2^\circ$
- Azimuth angle (horizontal deviation of drill line vertical plane from magnetic north); accuracy $\pm 1.5^\circ$

- Inclination angle (deviation of drill line from vertical); accuracy $\pm 0.25^\circ$

Equipment performing these functions (see Figure 6) consists of:

- $7\frac{3}{4}$ or $8\frac{1}{4}$ inch diameter by 34 feet long non-magnetic drill collar which serves as a housing for the complete telemetry system.

- Transmitter assembly which houses system prime power generating equipment as well as the downhole mud pulse generator.

- Directional drilling sensor assembly which contains the basic magnetic and vertical sensing instruments, the electronics associated with their operation, and signal and power processing equipment to complete the electrical interface with the transmitter assembly.

- Connecting cable assembly to perform the sensor-to-transmitter electrical connection and permit the sensor assembly to be located remotely from the magnetic interference of the transmitter.

- System isolation mounts which attach the equipment to the drill collar and protect it from shock and vibration.

- Surface equipment consisting of mud pulse pressure transducer, directional data and read-out instruments, and associated electrical cabling.

The downhole assembly was designed to withstand a downhole pressure of up to 17,000 psi, and a downhole temperature of up to 300°F. The original system operates with mud flow between 320 and 650 gpm. A modified system is currently being fabricated which will operate with mud flow up to 1,000 gpm.

Transmitter—The transmitter produces pressure pulses in the mud flowing through the drill string. It does this in response to digitally encoded electrical signals from the directional sensor by modulating the flow area of the mud valve through which all the mud flow passes. This valve is located at the upper end of the drill collar just below the upper suspension which secures the transmitter to the drill collar.

A secondary function of the transmitter is to provide power for the complete system. Power to operate the transmitter and sensor is derived from the mud flow by a turbine which drives an alternator and a hydraulic pump in the transmitter.

The alternator supplies the electrical power needed to operate sensor mechanisms and electronics, and a solenoid valve in the transmitter hydraulic actuator. The hydraulic pump produces the hydraulic power which actuates the mud valve.

The transmitter consists of the following basic components: upper suspension, mud valve, hydraulic actuator, alternator, compensating system, shaft seal, turbine and electrical connector to sensor (see Figure 6).

Upper Suspension—The transmitter is mounted to the inner wall of the drill collar through the upper suspension unit which consists of a number of elastomeric rings bonded to metal supports. Elastomeric bumpers limit the travel of the rings. The rings and bumpers

TELECO DOWNHOLE SYSTEM

FIGURE 6—Teleco Downhole system.

DETAILS:

1. 34 ft. 7 3/4 or 8 1/4 in. OD, 5 1/16 in. ID nonmagnetic drill collar.
2. Equivalent Stiffness:
 7 3/4 inch collar same as std. 7 1/4 OD x 2 13/16 ID collar
 8 1/4 inch collar same as std. 8 OD x 2 13/16 ID collar
3. Tool Joints:
 Box-Box: 6 5/8 API, Regular Thread (API-STD 7)
 Material: Servconel
 Recommended Maximum Make-up Torque: 40,000 ft.-lbs.
4. Pressure Drop Through 34 ft. Downhole Assembly: Approximately 100 PSI @ 450 GPM, Water

effectively support and cushion the transmitter from downhole shock and vibration.

Mud Valve—The mud valve is a poppet-type cone plunger which is centrally located at the entrance to the drill collar just below an orifice. In the retracted position, it offers essentially no restriction to mud flow; in the extended position it restricts the mud flow to create the desired pressure increase upstream of the orifice. See the section on principles of mud pulse telemetry for more details.

Hydraulic Actuator—The mud valve is extended and retracted by a hydraulic piston within the transmitter housing. The pressure required to actuate the piston is generated by the hydraulic pump, and the extension-retraction is controlled by a solenoid valve which is energized by electrical signals from the sensor.

Alternator—The alternator is driven by the turbine shaft, and provides all electrical power required by the downhole assembly. Its output is regulated and rectified in the sensor.

Compensating System—The hydraulic actuator and alternator are enclosed in a housing to protect them from the mud environment. The internal portion of the housing is connected to a bellows which is externally exposed to the mud. The housing is completely filled with fluid and sealed off. The bellows then maintains the internal pressure of the housing at essentially the same pressure as the mud. This simplifies the housing structure, which thus does not have to support downhole pressures; and the housing seals are exposed to low differential pressures. The bellows has enough movement to accommodate the fluid volume changes caused by downhole pressures and temperatures.

Shaft Seal—The turbine shaft extends from the mud turbine itself into the transmitter housing where it drives the alternator and hydraulic pump. A mechanical seal is used to seal the mud from the compensating system fluid.

Turbine—The turbine is a multi-staged device with rotors fixed to the turbine shaft and stators fixed to the turbine housing. All mud flow passes through the housing because the outer portion of the housing is sealed to the drill collar inner wall. The turbine is designed to operate at proper speeds over the range of mud flow rates expected.

Electrical Connector—An electrical connector between the transmitter and sensor is required because of the transmitter alternator output which is rectified and regulated in the sensor, and the sensor data output which controls the solenoid valve in the transmitter. The connection system has some flexibility because the transmitter and sensor are each independently suspended in the drill collar.

Directional Drilling Sensor—The function of the sensor assembly is to provide data which defines angular orientation of the drill string in the vicinity of the drill bit. The equipment involved consists of: (a) the sensing mechanism, and (b) the electronics associated with its operation. A modular concept is employed in the packaging of these functions which permits the sensing mechanism to be physically separated from the electronics portion of the sensor. This feature permits adaptation of the electronics functions for use with other parameter sensors. The existing directional drilling sensor assembly is housed in a pressure-proof cylindrical housing. Within the drill collar, the entire sensor assembly is suspended by means of elastomeric isolators to protect against shock and vibration.

The two subassemblies comprising the sensor assembly are described in the next paragraphs.

Sensor Mechanism—This portion of the sensor assembly contains the basic vertical and north sensing transducers used in determination of drill string orientation. These are specifically two pendulous accelerometers and one flux-gate magnetometer. The mechanical and electromechanical devices necessary for properly orienting the transducers during the directional measuring process are also a part of this assembly. Structurally, the sensor mechanism is housed in a cylinder. Only nonmagnetic materials are used in the

mechanism design. Extensive thermal, shock, and vibration tests have been conducted on the mechanism to assure its ability to withstand the downhole environment.

Sensor Electronics Assembly—The electronics portion of the sensor assembly contains the logic for conversion of the directional parameters into a digital code to be transmitted to the surface equipment. It also performs power conversions necessary for operation of the sensor assembly from prime power supplied to it by the transmitter assembly alternator. Packaging design of the electronics assembly employs conventional double-sided, conformally coated p.c. boards. The boards are contained in a housing and interconnected by a preassembled wiring harness. As was the case with the mechanism, a great deal of attention has been given to making the electronics as rugged as possible. Each and every component is carefully secured in place, wiring is encapsulated to the greatest possible extent, and lead ends are prevented from flexing during vibration. Vibration tests using resonance searches and dwells were employed to find and eliminate any potential weaknesses.

Surface Signal Detection and Display Equipment—At the surface, the mud pulse telemetry signal is received by a pressure transducer conveniently installed in the mud standpipe on the rotary drilling floor. The transducer is connected via a cable to a display box.

The display box contains electronic circuits for detecting, filtering, amplifying, and decoding the mud pulse telemetry signal. The display box provides a large, easy to read, lighted display of the three measured angles, tool facing ($\times \times \times^\circ$), inclination ($\times \times . \times^\circ$) and azimuth ($\times \times \times . \times^\circ$). It also provides for display of depth, which is entered manually by the operator. The displays are readable at 30 feet in sunlight.

A second electronics enclosure, which can be located remotely, contains a chart recorder and numerical printer which makes permanent records of the data. The records include actual mud pulse waveforms, and numerical records of tool facing, inclination, azimuth, depth, date and time of day.

FIGURE 7—Surface Electronic Equipment.

FIGURE 8—Operating Sequence.

Both electronics enclosures are heavily ruggedized and are designed for explosion-proof safety so that they can be located on the rig floor when so desired. A positive internal pressure is maintained within the enclosures by means of dry air or dry nitrogen pumped from a safe location. The surface electronic equipment is designed to operate on drill rig a.c. power between 80 and 125 volts and 55-65 cps.

Setting up the surface electronics is straight forward in that no critical adjustments or "fine tuning" is required. The system operates equally as well with duplex and triplex mud pumps.

SYSTEM OPERATION

Rotary Drilling—To obtain a survey the driller stops rotation for about 1½ minutes while maintaining mud flow constant. He may reciprocate the drill string once data transmission has begun if there is a danger of pipe sticking. In the downhole assembly, a sensing device recognizes the halt in rotation, signals the directional sensors to begin measuring the tool facing, inclination, and azimuth angles, and activates the transmitter which begins sending a preamble message (an initial series of pressure pulses) to the surface. The preamble message activates and synchronizes the surface detection equipment.

While the preamble message is being transmitted, the sensors acquire their first measurements, the data for which is stored electronically, and after the measurements are completed the transmitter begins to send the data to the surface.

Once data transmission begins, the driller may resume rotary drilling. Each angular measurement requires about 50 seconds for transmission, so that sending up a complete set of three angles takes 2½ minutes.

As long as the drill string is stationary, the sensor will continue to make new measurements of the directional angles, store the data, and send it to the surface via the transmitter. If the operator wants a second set of survey readings for verification, he continues to hold the drill string stationary while the first set of readings is being transmitted (see Figure 8). In this case, the rotation sensor permits a new measurement cycle to begin during transmission of the first set of data. Transmission of the second set of data begins immediately upon completion of transmitting the first.

Once the operator resumes rotation, the sensing mechanism is de-activated by the rotation sensor and the transmitter shuts off after transmitting the most recently acquired set of readings.

Interruption of mud flow will likewise terminate a transmission, and resumption of mud flow without rotation will start a complete new cycle including the preamble message.

Mud Motor Drilling

When the Teleco system is operated with a mud-powered drill such as a Dyna-Drill or a turbine drill the system operates continuously as long as mud flow is maintained. This provides a continuous display of inclination, azimuth, and tool facing while drilling.

The Teleco system is particularly useful during well kick-off with a device such as Dyna-Drill. Continuous monitoring of tool facing allows the driller to compensate for drill string wind-up using real data rather than rules of thumb. Thus proper tool orientation is much easier to maintain. Continuous monitoring of inclination and azimuth allows the driller to observe and control the build-up of angle and direction according to the plan for the well.

PILOT SERVICE DEMONSTRATION PROGRAM

Summary

The following paragraphs summarize the results obtained during the first half of a 12-month Pilot Service Demonstration Program. Through January 1978 performance of the Teleco tool has been demonstrated in the directional drilling of seven wells involving three of the six oil companies participating in the program. The tools have seen service in the field during both jet and mud motor kick-offs, and have been used to monitor well course progress and aid in course corrections to a maximum measured depth of over 12,000 feet.

Well inclinations of up to 50° have been experienced. Azimuth direction angles of wells using the equipment have been distributed throughout almost a full 360°. Acceptance of the tool usage and reliance on its survey data by the directional drilling personnel involved in the demonstrations has been enthusiastic. Correlation between Teleco surveys, gyro surveys, and single-shot surveys has been excellent.

Detailed Test Results

Hours of Operation—So far in the demonstration program tools have accumulated a total of over 900 hours of mud circulation. Of this total, 800 hours are from operation during the two-month period immediately preceding this writing.

Drilling Details—Directional wells involved in the Teleco equipment tests have been characterized by a variety of situations. Survey data was provided before, during, and after kick-offs from depths ranging from approximately 700 to 6,800 feet (M.D.), with subsequent angle builds to as high as 50°.

Four of the kick-offs experienced were via Dyna-Drill; two were by jetting. In all cases reliance on Teleco survey data by directional drilling personnel was heavy. In one jet kick-

off, where prior USGS approval had been obtained, Teleco data were used exclusively for jet orientations. In other instances supplemental single-shot surveys were taken only as frequently as was necessary to comply with USGS minimum requirements.

Hole course directions at the various well sites included all four azimuth quadrants. The Teleco survey tool was used frequently during directional steering after kick-off to monitor hole course for anticipated walking into the desired azimuth direction. In several cases this did not occur as anticipated. The situation was detected early by the use of frequent Teleco surveys, thereby alerting the directional driller to take prompt corrective measures.

The tool was used throughout the drilling operations to provide such a monitoring function, and was very useful in detection of small angle changes, with resulting early course corrections to keep the hole closely on line. Teleco surveys were taken as frequently as 2 or 3 pipe lengths even in those portions of the well where surveys ordinarily would have been taken only at extended intervals.

Two of the wells involved in the seven tests conducted thus far were drilled in formations where unanticipated course deviations were frequent. In one such case three Dyna-Drill course corrections and one jet correction were prompted by the use of Teleco tool monitoring. The time required to obtain such close control of well course by conventional methods would have been prohibitive.

A representative comparison of Teleco surveys with that of single-shot surveys is shown in Figure 9.

Some interesting observations have been made as a result of frequent surveying. In one case, during close course monitoring shortly after kick-off, an inclination angle change of 2° was indicated after drilling only 30 feet. The severity of the dogleg involved in such a high rate of change caused the validity of the survey to be doubted. However, the dogleg was verified by returning to the same points sometime later and repeating the surveys.

This same sharp inclination angle change had also been observed on at least two other occasions. The same rapid change in inclination, though not to the degree cited in the above example, can be seen in the plot of Figure 9, as depth increases from 5,600 feet to 5,700 feet.

As mentioned earlier, Teleco survey data is recorded on a print-out chart in the surface equipment assembly, along with a strip chart record of mud line pressure as sensed by the mud pulse pressure transducer. This is done primarily to provide a permanent record of directional monitoring and the quality of data pulse transmissions.

Thus far in the demonstration program, the pressure monitoring function has produced some interesting side benefits. It has been used to diagnose bad valves in the mud pumps in one instance, and to pin-point faulty pulsation dampers in another. It has indicated a stalled mud motor, and given early indication of partial pressure loss due to joint wash out on other occasions.

Survey Comparisons—Typically, at the conclusion of a field test a comparison is drawn between the bottomhole locations as computed from the Teleco survey data, the single-shot data, and the multi-shot data. At the time of this writing complete data sets for all of the seven wells logged thus far in the demonstration program are not yet available.

A representative three-way comparison of the data from Test No. 1 is shown in Figure 10A. Shown in Figure 10B is a similar comparison made after the last test of Prototype Test Series. In these examples bottomhole location comparisons were calculated by the radius of curvature method assuming identical initial locations.

The three sets of data will, of course, result in a triangular fix. Agreement between any two points of the triangle has been excellent, normally between 10 feet to 30 feet. We have seen no evidence to suggest that any two sets of data consistently provide greater agreement than any other two sets of data from the same well.

In this regard the two examples given in Figure 10A and Figure 10B are typical. In

FIGURE 10A—Bottom-hole location comparison, PSD No. 1.

FIGURE 10B—Bottom-hole location comparison, prototype field test #31.

Figure 10A the gyro data is in closer agreement with the single-shot data than it is with the Teleco data. In Figure 10B the Teleco data is in almost exact agreement with the gyro data. The preliminary conclusion we draw is that the accuracy of the three survey techniques is comparable.

Significant Achievements

- Successive tool runs of 254 and 272 hours without maintenance or malfunction.
- Close agreement among Teleco, single-shot, and multi-shot survey readings.
- Ready acceptance of the usefulness of the system by directional drillers.
- Approved USGS usage—USGS approval was granted for use of Teleco survey data without a back-up single-shot (1) during a jet kick-off and (2) during directional drilling of the last 3,000 feet of the same well.
- Reduced survey time.
- Reduced orientation time (kick-off with mud motors and jet deflection) more frequent directional measurements.

CONCLUSIONS

1. Mud pulse telemetry has been shown to be a practical communications link for transmitting directional drilling data from the bit to the surface while drilling.
2. The communications link is extremely reliable even while rotating and drilling. Mud pulse telemetry therefore can be used to communicate other measurements while drilling such as formation properties, bottomhole mud properties, and drilling parameters.
3. Accuracy of Teleco surveys, made during the drilling operation, compares favorably with single-shot and multi-shot surveys.
4. It has been demonstrated that telemetry of directional data offers significant

savings in rig time. Other benefits, accruing through the timely availability of more frequent and accurate survey data may prove to be equally important. Further field experience is required before these secondary benefits can be fully evaluated.

5. The downhole drilling environment particularly long term vibration, shock, and abrasive drilling mud, is extraordinarily severe. In many respects the task of developing equipment for this environment represents an even greater engineering challenge than found in aerospace and other high technology fields which demand extremely high equipment reliability.

6. Equipment consisting of advanced electronic components, mud powered turbine generators, long life seals, and moving parts hydraulic devices can all be designed to operate reliably in the downhole drilling environment.

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Cochran Dean Co.
Eastman-Whipstock Inc.
EMCO-Directional Drilling & Well Survey
Kajan Specialty Co.
Oil Well Drilling Control
Wilson Downhole Services

References

For further discussion and explanation of several of the key components described in this paper we refer the reader to the following patent literature:

TOPIC	U.S. PATENT NUMBERS	
Directional Sensors	3,982,431	4,021,774
Rotation Sensor	4,013,945	
Vibration Isolators	3,782,464	3,714,841
Hydraulic Valve	3,756,076	3,693,428
Actuator	3,737,843	3,958,217

PSD NO. 2

FIGURE 11—PSD No. 2.

PSD NO. 3

FIGURE 12—PSD No. 3.

ADDENDUM

Following preparation of the original manuscript for this paper, additional comparative survey data were obtained permitting us to show the following added comparisons.

Figure 11

This figure shows the bottomhole coordinates for Teleco's Pilot Service Demonstration No. 2, as computed from conventional single-shot data, gyro multi-shot data, and Teleco data at a measured depth of 11,060 feet. The circle on the diagram represents the 200 foot diameter bottomhole target area. Teleco survey readings were accurate and consistent, and the directional engineer relied upon the Teleco data to a large extent.

Figure 12

Figure 12 shows a similar set of bottomhole coordinates from Demonstration No. 3 and the bottomhole target, 500 feet in diameter. In this case there were no multi-shot data available. Confirming single-shot surveys were taken only as frequently as dictated by minimum USGS requirements. During a jet kick-off at approximately 700 feet, jet orientation information was obtained almost exclusively from the Teleco system. A final multi-shot survey was deemed unnecessary.

Figure 13

As shown earlier in Figure 8 Teleco survey data can be acquired in just a few minutes, as opposed to the length of time needed for a single-shot survey. Thus, the Teleco system provides the directional driller with the opportunity for much more frequent surveys. This is illustrated graphically in Figure 13. Here the ratio of Teleco surveys (dots in the Figure) to single-shot survey (dashes) is at least 3 to 1. This indicates that the directional driller wants much more frequent survey data than he can afford to obtain by the single-shot method. This allows the driller to do a better job of staying on the planned course.

Figure 14

Figure 14 shows bottomhole coordinates for Demonstration No. 5 and the bottomhole target, 500 feet in diameter. In this case the data include Teleco surveys and the final gyro multi-shot. The Teleco tool was used exclusively to make a jet kick-off at around 700 feet with USGS approval. USGS also approved drilling the final 3,000 feet of hole with exclusive use of the Teleco system, and therefore there is insufficient single-shot data to show in the figure. In this case and also for Figure 11 the gyro multi-shot survey was performed in the open, uncased hole.