USE OF AUTOMATED LOGGING UNITS FOR PREDICTING ABNORMALLY PRESSURED FORMATIONS AND WELL CORRELATION

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INTRODUCTION

Recent field tests in South Louisiana have culminated a three-year research project by Baroid. The project objective was to apply the computer expertise developed while producing Baroid's CDC (Computerized Drilling Control) units introduced in 1971[1] to the development of an automatic pore pressure logging system. The CDC units require crews of up to seven people. The proposed system was to require only three crew members through more reliance on the computer for data collection, analysis, and presentation.

The system (now designated Automatic Logging Service - ALS) evolved through several distinctive developmental phases. The first was the theoretical phase in which a mathematical model of the drilling operation was developed. This phase was reported by Bourgoyne and Young in 1973.[2] The second phase consisted of field-testing the model through use of electronic calculators at the well site. The third phase was to implement the model in software for a mini-computer designed for real-time operation. The fourth and recently completed phase was to field-test the complete equipment and software package system.

The ALS unit is designed to use a modern digital mini-computer, sensor devices, a system of mathematical equations, and one operator per tour to produce a pore pressure log on a continuous basis while drilling. Computer system responsibilities include data monitoring, storage, analysis, and presentation. Data collection is accomplished through the use of rig-mounted transducers that monitor the drilling parameters and transmit analog signals to conditioning panels. These panels then convert the transducer outputs into computer compatible signals. The computer reads and scales these values into engineering units. Parameters being automatically monitored are depth, hook load/bit weight, rotary speed, pump strokes per minute, on/off bottom, catalytic mud gas, and thermal mud gas. Parameters manually entered into the computer are mud density, shale density, sand/shale percent, and pertinent wellbore constants.

Drilling data storage is accomplished through the use of a magnetic cassette tape unit that is fed from the computer on a time and event basis. Events that cause tape records to be generated are: the beginning of a bit run, the end of a bit run, the completion of a drilling interval, and the completion of a lag interval. During drilling, data averages are accumulated until an interval is completed. These averages are then stored on the tape. Records are created of certain data lag arrays on a time basis to minimize loss due to power failure. These lag arrays are dumped onto tape every 15 minutes. The system recovery program, following a power outage, automatically reads the most current lag array record into memory. The format of the stored data permits easy on-site utilization.

Data analysis is done by applying the drilling model and drilling response equations. Drill rate is computed from the depth and on-bottom signals for several interval sizes (1, 2, 5, and 10 feet) and flow rate is computed from pump strokes. The Jorden and Shirley[2] "d" exponent and a modified "d" exponent are computed. Hydraulic jet impact force, equivalent circulating mud density, bit tooth wear, and drillability are also computed. The most important computed parameters are pore pressure and drilling porosity.

Data presentation is handled by the computer through the use of two computer peripherals, a keyboard printer and an X-Y plotter. The printer produces typed reports of the various monitored and computed parameters on a depth interval basis (see Appendix). The plotter presents a continuous log of various curves such as normalized drilling rate, mud gas, lithology, porosity, and pore pressure (see Figs. 1-9). The plotter has the capability of backing up to handle lagged parameters such as lithology and lagged pore pressure. It can also inscribe depth numbers and print special messages on the log. Depth numbers are written onto the log automatically while the messages are written after the operator enters the message and the X and Y coordinates of the message.

Through use of the stored data and the plotter an important system capability is realized, "re-drilling". The system of analysis equations is designed so that the origin of the data being processed is unimportant. Data retrieved from tape are processed exactly the same as real-time data. Thus, at the conclusion of a bit run, the interval may be "re-drilled" from tape with different constants being applied in the equations. This "re-drilling" allows the operator to calibrate the produced log to correlate with offset wellbore information.

The responsibilities of the lone operator include: transducer maintenance, program loading and initiallization, limited sample catching and analysis to determine shale density and the sand/shale ratio, and drilling model "tuning". The drilling model is periodically adjusted through changes in the various constants to fit the current formation, bit, and hydraulics conditions.

THE COMPUTER SYSTEM

The computer system which includes both hardware and software consists of these main parts:

1. Computer Main Frame—A mini-computer with 16K words (16 bits/word) of memory, sixteen channels (13 bits/ ±10V) of analog-to-digital capability, and a real-time clock.
2. Secondary Storage—A dual-head magnetic cassette tape unit that has a write speed of 600 bytes per second and read speed of 2500 bytes per second. The dual head feature provides immediate device back-up.
3. Plotter—An X-Y plotter that utilizes a single chart paper roll attachment.
4. Keyboard Printer—A thermal keyboard printer that operates at 30 characters per second.
5. Real-Time Operating and Monitoring System A vendor-supplied software package has been extensively modified to include "Human Engineered" operator aids. The operating system handles program scheduling, foreground/background computation, interrupt handling, and all required operator keyboard functions. Input data is read, scaled to engineering units, and sent to the drilling model for processing.
6. Drilling Model and Regression Analysis—A system of mathematical equations developed by Bourgoyne and Young.[2]
7. Off-line "Re-drilling" Capability—A program that may replace the real-time monitoring system as the drilling model's source of input data. It allows the operator to select and replot, using the same or different regression analysis constants, any previously monitored depth interval. The drilling model may be "calibrated" to off-set logs by simply replotting with different constants until a satisfactory correlation is established. An example of model "tuning" is shown in Figs. 1-5 in which an actual transition zone is "re-drilled" while varying the formation strength parameter a_1. It should be noted that a normal "tuning" operation on a_1 would involve changes of only ± 0.2. The example replots utilize a much wider range to dramatize the effect of such constant changing. Figure 1 shows that using $a_1 = 2.50$, the model predicts a pore pressure of 12.3 ppg at 9600 ft. Figure 2 shows $a_1 = 2.93$, producing a computed pore pressure of 11.6 ppg. Figure 3 shows $a_1 = 3.10$, producing a computed pore pressure of 11.3 ppg. Figure 4 shows $a_1 = 4.00$, producing a model-computed pore pressure of 9.8 ppg. Figure 5 shows $a_1 = 5.00$, producing a pore pressure prediction of 8.1 ppg. The actual pore pressure was estimated from the electric log of the interval to be approximately 11.5 ppg. The a_1 range for the Gulf Coast area has been established as 2.71 to 3.78[1]; hence, normal "tuning" would start at about 3.20 and work out from this base in increments of ± 0.1.

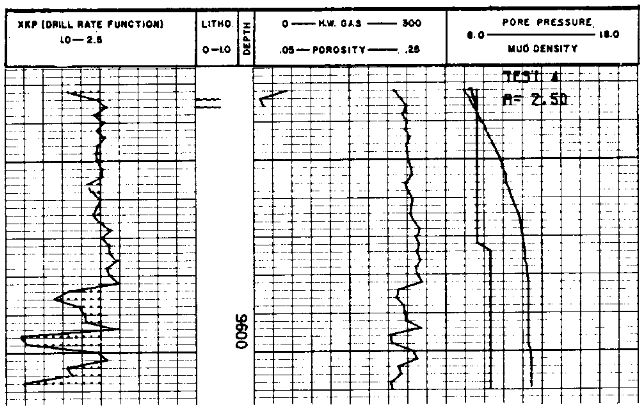

FIG. 1—"RE-DRILLING" AN INTERVAL WITH a_1 = 2.50

Plotter outputs are: *Left Track;* drillability (KP) dotted lines indicate current sand/shale base line, *Depth Track;* bar graph of lagged sand/shale percent and inscribed depth numerals, *Middle Track;* lagged mud gas (left side) and drilling porosity (right side), and *Right Track;* mud density (straight lines), computed pore pressure (curved line), and optionally undated pore pressure (curved line plotted on the lagged depth coordinate with sand/shale percent and mud gas).

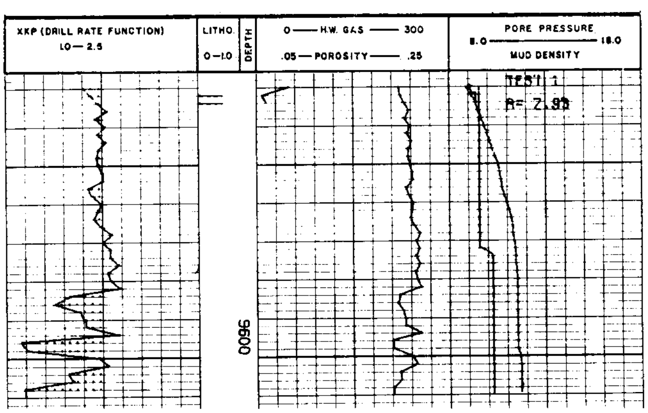

FIG. 2—"RE-DRILLING" AN INTERVAL WITH a_1 = 2.93

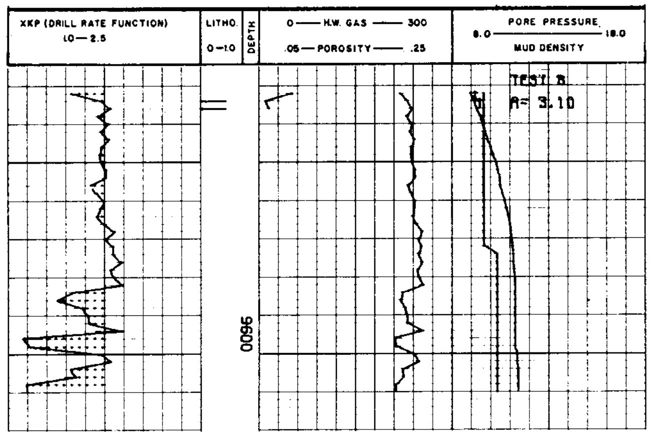

FIG. 3—"RE-DRILLING" AN INTERVAL WITH a_1 = 3.10

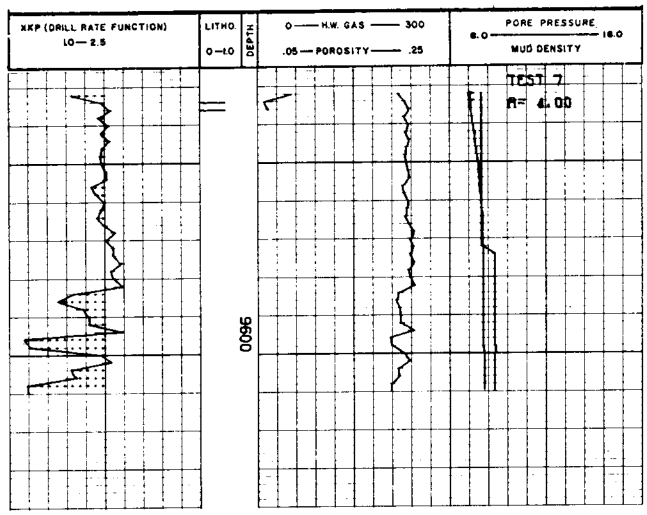

FIG. 4—"RE-DRILLING" AN INTERVAL WITH a_1 = 4.00

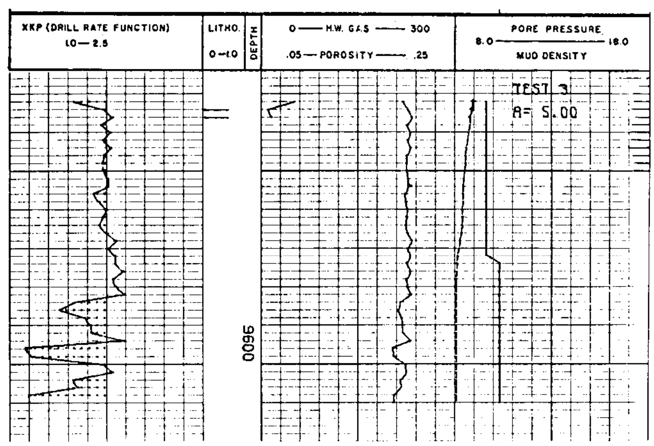

FIG. 5—"RE-DRILLING" AN INTERVAL WITH a_1 = 5.00

HUMAN ENGINEERING

Human engineering has been applied throughout the system both in the transducer panel and the software system as recommended by Taylor.[4] Indicator lights tell the operator that the pump strokes, depth, and on/off bottom signals are being properly sent to the computer, simplifying troubleshooting. Test signals may be fed to the computer for the bit weight and rotary speed panels to aid the diagnosis of problems. These test signals simulate the transducers, allowing immediate determination of trouble source (panel or transducer/cable). The unit is centrally air conditioned and heated for operator comfort and equipment performance.

The software data entry and program activation sequences have been subjected to much analysis to determine methods to minimize operator training time and potential operator error. The original vendor-supplied system functioned only in octal addresses and data values. A decimal input program was found to be necessary early in the development. Due to the memory utilization of the operating system the primary initiallization constants are scattered through memory. Requiring the operator to accurately change addresses to input the data string proved to be unsatisfactory. A special initial data input program has been developed that automatically skips through memory following the format of the input data sheet. Common errors such as typing a letter "O" instead of the number zero or striking an unnecessary decimal point are handled by sounding an audible signal on the keyboard and ignoring the input. The entire program loading, tape positioning, and data entry sequence is conversational except for the basic system bootstrap operation which still requires manipulating the computer front panel switches.

A design objective of the project was the ability to train a logging engineer to use the computer system in one day. Our CDC experience had shown that some competent field people have great difficulty in learning to use the computer. These personnel often decided early in the training session that the computer was simply too complicated for them to master. Once they made up their minds, it truly was too complicated. With this constraint on the design of the system, a large portion of software development time was consumed by "operator ease" programming.

Human engineering was also applied to the data presentation. A sample depth interval report is shown in the Appendix. Note that easily memorized abbreviations are used for the various parameters. Many of these values are of interest to the drilling fluid engineer, rig supervisor, geologist, and others at the well location in addition to the operator; thus the use of nonlabeled columnar data was abandoned. Off-line programs are available that will generate headed, paged, and columnarized data from the data tapes.

SYSTEM OPERATION

The pore pressure log may be generated in two modes, real-time and off-line. The real-time mode occurs during drilling. The drilling model processes the data at the completion of each drilled interval (selectably 1, 2, 5, or 10 feet) and computes normalized drill rate, porosity, pore pressure, and updated pore pressure (utilizing lagged parameters). The log is drawn on a standard API well log format that is 8.5 in. wide and has three main tracks each 2.5 in. wide. A small 1.0-in. track is normally reserved for labeling depth. Shown in Fig. 1 is the usual arrangement of parameters plotted on the log. However, the software allows some flexibility in the choice of parameters plotted. In the first track, the operator may select (1) normalized drillability on a log (base 10) scale, (2) normalized drillability on a linear scale, (3) observed drilling rate (ft/hr), (4) "d" exponent, or (5) modified "d" exponent. In the depth track the operator may also plot a bar graph of lithology (percent sand/shale). Mud gas is always plotted in the third track with catalytic gas scaled from 0 to 250 units and thermal gas scaled from 251 to 3000 units. The operator may also plot (1) computed drilling porosity, (2) formation density, or (3) formation factor in the third track. Mud density and pore pressure are plotted in the last track. Optionally, updated pore pressure may also be plotted in the last track.

In the real-time mode the logging engineer initially must select the starting drilling constants, either by estimation (selection from the range established for the area) or from offset ALS logs. Once drilling starts, these constants may be (1) allowed to dynamically change through use of regression analysis, (2) held constant throughout the interval, (3) manually changed during the interval, or (4) held constant for a time, then allowed to regress. The real-time log is a work sheet with the final log developed later by the off-line replot of the drilled interval.

In the off-line mode the operator may change the constants as in the real-time mode or he can plot the entire interval using one set of frozen constants and then replot using a different set. Figures 1-5 show an example of an interval that was repeatedly replotted ("re-drilled") while changing only one constant.

During the actual drilling operation the ALS operator may choose the interval size to be plotted based on expected drilling rates and lithological considerations; however data are collected and recorded on a one-foot interval regardless of the selected interval. This allows off-line plotting to have interval size selectability. Often, a fast-drilling section may be plotted on a 5-ft interval size to smooth out the curves, while later it may be desirable to see the entire data spread. Figures 6-8 show examples of a section of hole that was "re-drilled" on 1, 2, and 5 ft intervals. The plotted log may be on 5.0 in./100 ft or 1.0 in./100 ft. Normally the 5.0 in./100 ft scale is used during drilling for maximum visibility and easier correlation, while the 1.0 in./100 ft log is used for compositing multiple bit runs. Figure 9 shows an example interval plotted on the 1-in. scale.

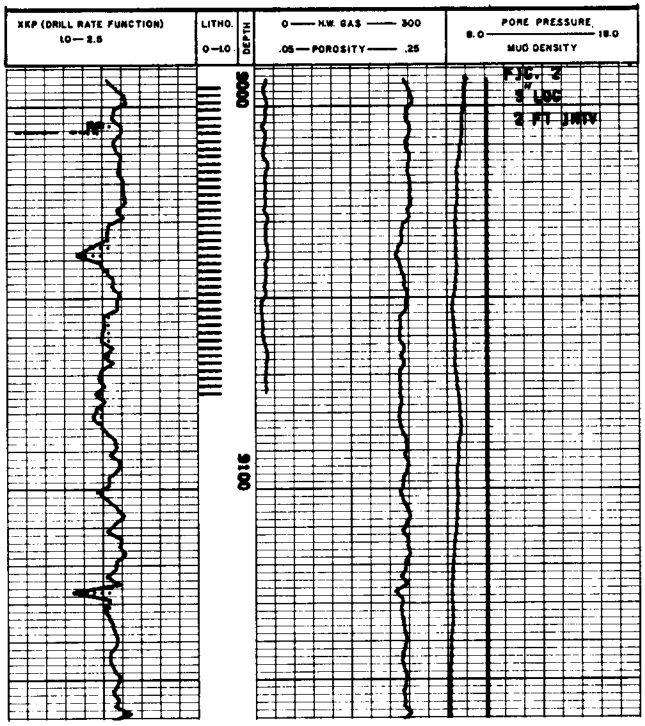

FIG. 7—AN INTERVAL "RE-DRILLED" USING A 2 FT INTERVAL SIZE AND 5 IN./100 FT SCALE

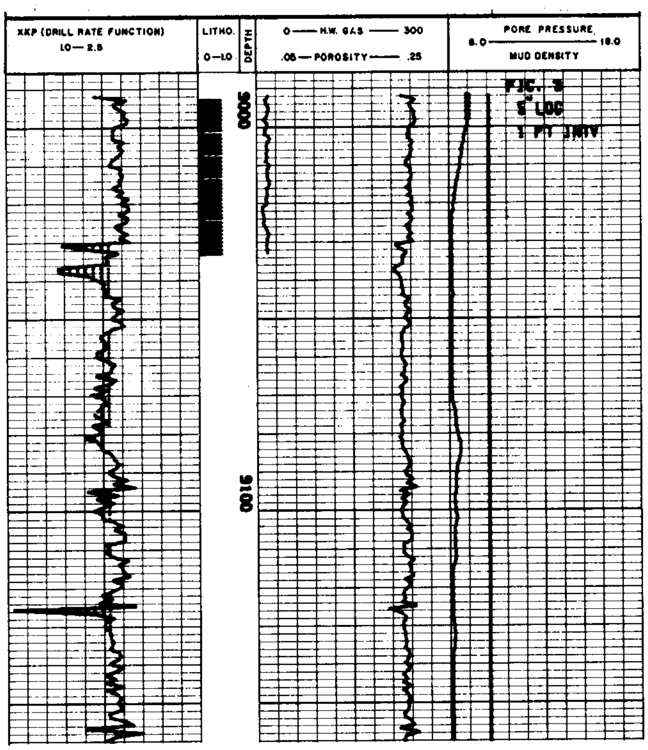

FIG. 6—AN INTERVAL "RE-DRILLED" USING A 1 FT INTERVAL SIZE AND 5 IN./100 FT SCALE

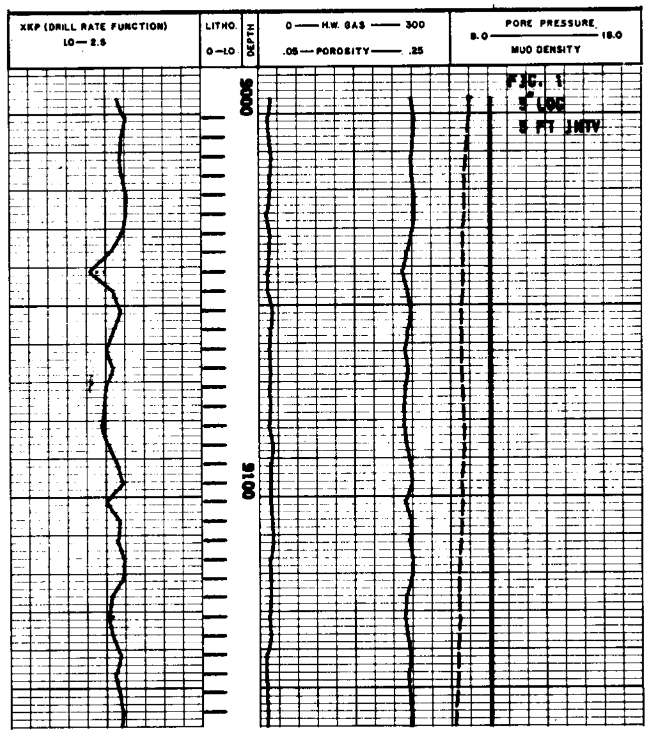

FIG. 8—AN INTERVAL "RE-DRILLED" USING A 5 FT INTERVAL SIZE AND 5 IN./100 FT SCALE

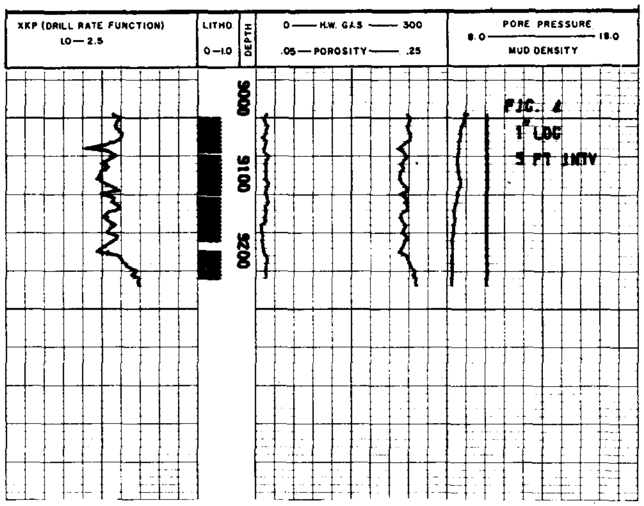

FIG. 9—AN INTERVAL "RE-DRILLED" USING A 5 FT INTERVAL SIZE AND 1 IN./100 FT SCALE

Regression analysis is possible during the off-line plotting. Actually, much regression analysis is done off-line since it is easier to pick the shale sections to be used for the analysis after drilling the interval. During the trip, a drilling study is performed to "tune" the model to the current drilling conditions so that a "calibrated" model may be applied at the beginning of the next bit run.

The off-line "re-drilling" mode offers the following options:

1. Multiple regression analysis may be performed using different constants.
2. Different parameters may be plotted.
3. The interval size may be changed for more or less lithological sensitivity.
4. The log scale may be 5.0 or 1.0 inch per 100 ft of hole.

DRILLING MODEL TESTING

The drilling model has been tested at several levels. The first level testing was performed in-house through the use of data manually collected on specially designed data sheets. These data sheets were designed in keypunch form so that data recorded at the well site by the logging engineer could be submitted directly to the computer keypunching personnel. These sheets were distributed to field personnel at selected sites. Data were collected for several months and punched onto cards. These cards then formed the basis of the large-scale multiple regression analysis which ultimately yielded the current drilling model.

The system of equations forming the model was then programmed into a desk top calculator and taken to the field. Approximately 50,000 ft of hole were monitored in South Louisiana and the data subjected to calculator analysis. This analysis was done on-site, during drilling, with the operator subjectively selecting the shale section of interest prior to applying regression analysis. Early weaknesses were corrected and an overall pore pressure accuracy of ±1.0 ppg was reported for the calculator equations. It should be noted that the subjectivity of an electric log-derived pore pressure forced the 2.0 ppg range noted above. The computer pore pressure may have been exact in many sections of hole, but there was no way to confirm the actual pore pressure.

Following the success of the calculator application, the drilling model was programmed for the mini-computer. A significant problem is how to program the computer to effectively differentiate between sand and shale sections. In the calculator version the operator decided after passing through a section, not immediately during the drilling of the section. The problem is handled in the mini-computer by using a sand/shale drillability base line. This value is initially entered by the operator after selecting it, based upon current drilling conditions. As drilling proceeds, this initial value is modified by the system so as to follow current drilling progress. Only intervals with drillabilities within a certain percentage range of this dynamic base line are accepted for consideration in the regression analysis.

COMPUTER SYSTEM TESTING

The mini-computer version of the model has been tested on two wells and a sidetrack well in South Louisiana. The first well drilled near Eunice brought out a number of system weaknesses that were corrected prior to the second test. Only about 20% monitoring efficiency (monitored intervals divided by intervals drilled while onsite, times 100) was obtained due to program "bugs", panel problems, transducer failure, and operator inexperience. The second well produced an immediate monitoring efficiency of 80% for the first week on site with an improvement to 95% within two weeks on site. The remainder of the second well and the later sidetrack of that well produced efficiencies of 90-95%. It should be noted that in the oilfield environment a consistent 95% monitoring efficiency is probably the maximum obtainable with present instrumentation. The hook load/bit weight load cell will slip on the deadline, wind will blow the depth follow line or it will break, the unit power source will fail, or the gas detector filament will burn out, all causing potential data loss in the range of 5%.

The results of the second well were that an approximate 1.5 ppg transition zone was drilled and not detected in the real-time mode because of the use of an improper regression constant. This transition zone is shown in Figs. 1-5. The later "re-drilling" of the zone with the proper constant produced an unmistakable transition curve (see Fig. 2). The operator had changed the constant in question (a_1) due to his inexperience with the system. Since an electric log of the transition zone, as well as the ALS log, had been obtained, the sidetrack presented the ideal test situation since almost total offset data was available.

The results of the sidetrack hole were satisfactory. The interval in question was drilled with a 12.0 ppg mud, and computed pore pressure reached a maximum of 11.4 ppg. No mud gas was detected. Estimations of pore pressure from the electric log indicated that the computer-generated value was correct. The important feature of this application is the fact that an accurate pore pressure is being computed each interval, hence is immediately available for use by the rig-site personnel.

LIMITATIONS AND CONCLUSIONS

Several limitations of the ALS system should be noted. First, even though work to date is very promising, only data from the Gulf Coast area were used in the drilling model development and nearly all model testing was done in this area. Secondly, an early project objective to build a totally automatic (no subjective operator decisions or sample catching) pore pressure log has not been realized and may not be possible (but we're not convinced!). Work is continuing to improve the drilling model to reduce the required operator skill level. The ultimate system should calibrate itself while drilling and require no sample catching and analysis.

The application of a one-man-computerized-pore-pressure-logging (ALS) unit shows much promise for use on wells in the Gulf Coast area where the sample catching and mud monitoring of a mud logging unit are not deemed necessary and costs prohibit the use of the more complete monitoring units. Shallow wells and wells being drilled in production fields where abrupt transitions are expected are potential applications for such service.

In summary, the following has been done:

1. A drilling model of the Louisiana Gulf Coast area has been developed that utilizes multiple regression analysis.
2. This model has been implemented in a desk top calculator version and tested on approximately 50,000 feet of hole.
3. This model has also been implemented in a mini-computer and programmed to run in real-time mode with automatic regression analysis possible.
4. An immediate real-time pore pressure can be computed in South Louisiana with an apparent accuracy of ± 1.0 ppg.
5. The problem of developing an absolute algorithm to determine whether sand or shale is being drilled has been attacked but an absolute solution remains to be developed.
6. A mini-computer is provided at the well that supplies considerable on-site computing power for many potential uses such as off-line electric log data evaluation, pressure control calculations, and drilling cost analysis. Almost anything that can be done in large scale computers can be done in this mini, with execution time being the only limitation.

NOMENCLATURE

a_1 - formation strength parameter
a_2 - exponent of the normal compaction trend
a_3 - under compaction exponent
a_4 - pressure differential exponent
a_5 - bit weight exponent
a_6 - rotary speed exponent
a_7 - tooth wear exponent
a_8 - hydraulic exponent
d - bit diameter
D - hole depth
F - bit hydraulic force
H - bit tooth wear
KP - normalized drillability
N - rotary speed, rpm
p - equivalent circulating mud density, ppg
P - pore pressure, ppg
R - drilling rate, ft/hr
Sm - matrix strength factor
w - bit weight, 1000 lb
ϕ - drilling porosity, percent

$$KP = \mathrm{Log}_{10}\ R/\mathrm{Exp}(a_5x_5 + a_6x_6 + a_7x_7 + a_8x_8) \qquad (2)$$

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APPENDIX

The Printed Interval Report

A sample report is shown below with the data description list. These reports are generated automatically by the system as drilling progresses and the selected monitor interval is completed:

01:42:30

D	15030	DR	9.4	WB	30.00	N	100.0	Q	285.5
FJ	588	H	1.00	DX	1.811	MD	.952	KP	1.398
BS	1.403	PO	.206	EC	17.13	P	15.51*	P2	15.50
DL	15007	GS	15.90	C1	.05	FD	2.40	NM	19
RG	0	A1	4.05	A3	.00003	A1	31.73	A3	.00143

As shown above, the output consists of the time of day in hours (0-23), minutes (0-59), and seconds (0-59) followed by five lines of five numbers each. The data description is as follows:

<u>Line 1</u>

D - Current well depth, ft
DR - Average drilling rate of the logging interval, ft/hr
WB - Average bit weight of the logging interval, 1000 lb
N - Average rotary speed of the logging interval, rpm
Q - Average pump flow rate of the logging interval, gpm

<u>Line 2</u>

FJ - Average hydraulic jet impact force of the logging interval, lb
H - Fractional tooth wear at the end of the logging interval (0.00 for new bit to 1.00 for completely worn teeth)
DX - "d" exponent of the interval computed from averaged data
MD - Modified "d" exponent for the interval
KP - Normalized drillability parameter defined by Eq. (2) in Nomenclature

<u>Line 3</u>

BS - Computed baseline drillability, the sand/shale decision line
PO - Drilling porosity, percent
EC - Equivalent circulating mud density, lb/gal.
P - Computed pore pressure, lb/gal. (an asterisk (*) printed after the value indicates that P was computed for that interval - not a sand interval)
P2 - Updated pore pressure, lb/gal. (depends on data from examined cuttings - C1)

<u>Line 4</u>

DL - Logged depth correlating with mud presently at the surface (Lag depth)
GS - Mud gas, API units (Catalytic gas for 0-250, thermal gas 251-3000)
C1 - Shale fraction of the cuttings from the last sample, percent
FD - Formation density, gm/cc from last cutting sample
NM - Number of shale logging intervals that have been included in the regression analysis

<u>Line 5</u>

RG - Flag
A1 - Value of A_1 if Flag RG = 1
A3 - Value of A_3 if Flag RG = 1
A1 - Value of A_1 if Flag RG = 2
A3 - Value of A_3 if Flag RG = 2

Line 5 is of interest to the operator only if he turns the regression analysis mode on and off depending on drilling conditions.