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COMPUTER ASSISTED WELL CONTROL FOR DEEP OCEAN ENVIRONMENTS

by

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ABSTRACT

A study has been completed to develop improved safety systems and procedures for reducing the risk of surface and underground blowouts in deep ocean environments. The deep ocean well control system developed has been designed to assist in the removal of kick fluids from the well bore by providing improved down hole pressure control during the well kill operation. Improved bottom hole pressure (BHP) control reduces the risk of a blowout by decreasing the potential for formation breakdown and for secondary kicks.

The tedious tasks of manually controlling the choke and mud pumps during the well kill process have been automated, affording the operators more time to focus on higher level decisions. A mud pulse telemetry system was incorporated in the test system to demonstrate that down hole data can potentially be used as the controlling parameter(s), eliminating the need to base decisions solely on surface pressures as is currently done. Inclusion of measurement-while-drilling (MWD) technology as part of the well kill operation expands the horizon for novel approaches in kick fluid removal from the well bore.

Development and testing of the system was completed at the Louisiana State University Petroleum Engineering Research and Technology Transfer Laboratory (PERTTL). A subsea-configured well simulating 3,000 feet of water and 3,000 feet of sediments and a 6,000 foot surface-configured well were utilized for testing. A test matrix inclusive of 20 natural gas kicks and in excess of 30 simulated salt water kicks was completed for system evaluation. Results indicate that BHP can be maintained to within ±20 psi, contrasting the ± 200 psi commonly incurred by experienced operators completing manual well control exercises utilizing the same facility. Not only is safety improved through better BHP control but also the reduction or elimination of repetitive and tedious tasks, such as pump and choke control, increases safety by alleviating operator stress.

INTRODUCTION

Today's technology within the oil industry supports exploration for new hydrocarbon reserves further offshore and at water depths approaching 7,000 feet. Well control planning has proven to be expensive and difficult to achieve when drilling in this environment, routinely requiring sophisticated well plans. However, increased well plan sophistication has not prevented the occurrence of kicks, the unintentional flow of formation fluids into the well bore. Maintaining proper control during a well kill operation is the focus of this study, realizing that loss of control can lead to either a surface or an underground blowout. Blowouts, the uncontrolled flow of formation fluids, can be catastrophic with the potential for loss of life, extensive environmental damage, waste of valuable natural resources, and loss of rig equipment.

Three geological phenomena, not inclusive of all factors, make well control for deep water operations much more difficult than for land. Those considered most important for this study include reduced fracture gradients for increased water depths, abnormally pressured formations commonly encountered at shallower solids penetration depths, and the frequent presence of natural gas as the formation fluid.

Figure 1 demonstrates the reduction in fracture gradients experienced offshore as compared to land operations. All fracture gradients shown are representative for solids penetration depths of 3,500 feet and are expressed in units of equivalent pounds-per-gallon (ppge). The reduced fracture gradients are basically a function of less dense sea water being present in lieu of solids, resulting in a reduction in the total overburden pressure at depth. As a consequence of the reduced fracture gradient, the margin for operator error and the kick fluid volume that can be safely removed from the well bore is diminished.

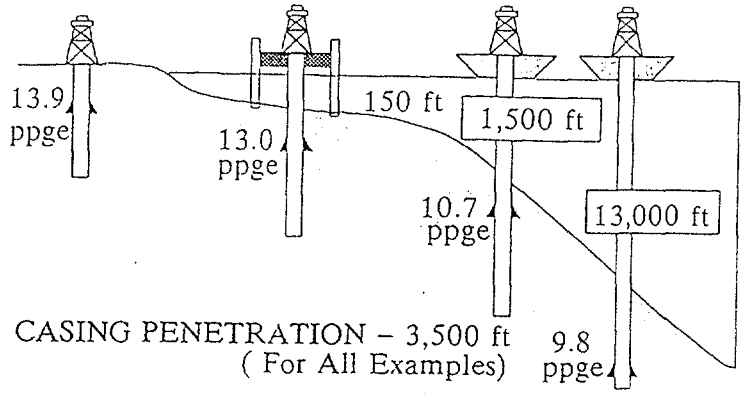

Figure 1 - Deep Ocean Formation Fracture Gradient Comparison

Accentuating the negative aspects of the reduced differential between drilling fluid and fracture gradients is the presence of abnormally pressured gas zones commonly found in deep ocean environments. ' Penetration of these zones expose the well bore to a higher-than-normal pore pressure gradients, so called abnormal pressure, creating higher-than-normal shut-in pressures that increase the potential for formation fracture. In addition, expansion of this gas during circulation causes annular fluids to be displaced to the surface. The resulting loss in annular hydrostatic pressure also forces the operator to maintain higher surface casing pressures. Underscoring the prevalence of natural gas offshore, Hughes, Podio, and Sepehrnoori (1987) reported that natural gas is the kick fluid for approximately three-fourths of all kicks occurring in outer continental shelf (OCS) waters of the Gulf of Mexico.

Protecting exposed formations from fracture for offshore operations is achieved through a more sophisticated and costly well plan, utilizing additional casing strings as compared to surface wells. Pore pressure and fracture pressure are instrumental in planning casing set points. However, the potential kick size and subsequent shut-in pressures, as well as the accuracy by which pressures can be controlled are important considerations when selecting casing points and are generally built into the well design safety factor. Obviously, the more precisely that pressure can be controlled during well kill operations, the better will be the utility of the well plan and safety margins designed. Industry well control exercises at PERTTL have repeatedly demonstrated the difficulty and the inconsistency by which experienced operators can reliably maintain constant BHP for the complex well geometries present in deep ocean drilling environments. As shown in Figure 2, fluctuations in BHP of 200 psi are routinely experienced during these exercises and in reality could lead to complications that increase the risk of formation fracture.

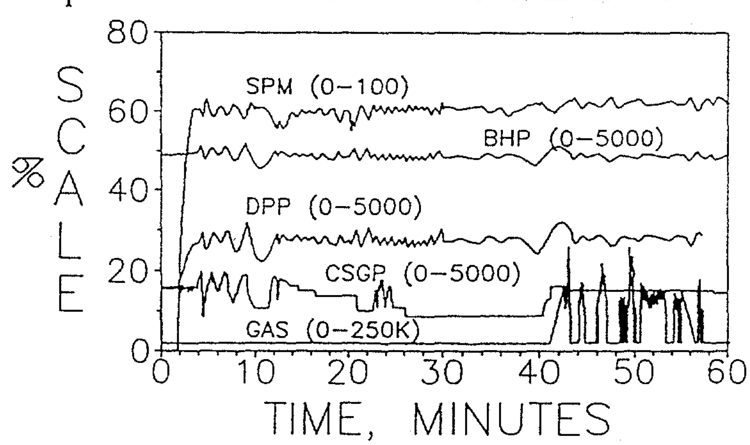

Figure 2 - Manually Controlled Subsea Well Kill Operation

These pressure fluctuations result from untimely and inaccurate control data and the inability of personnel to manually control the well bore dynamics on a real-time basis. Present technology for well control operations has not included the more advanced instrumentation and telemetry systems capable of providing this data and level of control. This inability to properly control BHP led to the initial proposal to study and make recommendations relative to well control for deep ocean environments.

OBJECTIVE

The objective of this study was to develop improved systems and procedures for reducing the risk of surface and underground blowouts for deep ocean environments. This objective is to be achieved through improved BHP control during well kill operations which will increase safety for rig personnel and equipment while reducing the potential for catastrophic environmental damage.

TEST PROGRAM DESIGN

Achieving the stated objective required evaluation of various systems, procedures, and human factors. Inconsistency in operator knowledge and expertise for completing a well kill, both planning and execution, has been demonstrated repeatedly in the well control exercises at the university. Four concerns were identified as weak points in the present well kill techniques being used and are as follows: (1) Numerous operators have difficulty with many calculations required to develop a well kill plan, (2) choke and pump operators often communicate inadequately during the well kill process, (3) operators are limited to knowing only surface pressures inferring BHP, and 4) operators are oftentimes faced with several hours of very tedious, stressful work.

Effecting a solution for the project involved the completion of several tasks. Step 1 involved collecting and storing data for use in the well kill program. Included in this data base are the well parameters that would be obtained from the daily drillers report and the frictional information taken each tour. Step 2 involved designing software to develop a well kill plan. Step 3 required developing computer control for the mud pump and choke systems. Step 4 involved developing software and down hole data input necessary to conduct a computer assisted well kill operation. Finally, Step 5 required the development of system flexibility such that manual control of the operation could be obtained without delay or difficulty, recognizing that being able to easily switch from computer assisted to manual control would be necessary for both safety and operator acceptance.

Figure 3 represents the conceptual design for the computer assisted well control system. New to well control would be the use of MWD down hole pressure data as a controlling parameter. The computer would be used for routine calculations, process control and collection of well parameter data such as drill pipe pressure (DPP), casing pressure (CsgP), and kill line pressures (KlP). Standard choke and rig mud pump systems would be used to control the well, but complimented by automated controls utilizing closed loop systems.

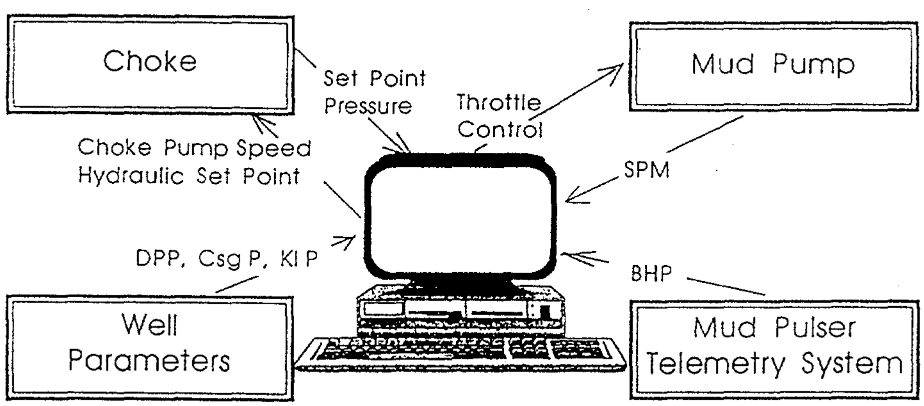

Figure 3 - Conceptualized Computer Assisted Well Control System

LSU's test well facility was configured as shown in Figure 4 and would be used to test the system under real-life conditions. As shown, the drilling fluid would be pumped down the well bore, returning through the choke and into the mud tanks. A gas storage formation simulator would inject gas kicks at a depth of 6,000 feet with a pressure sensor on bottom for collecting BHP data. These data could be available for use in the well control software once encoded, pulsed, and decoded. It was anticipated that BHP data would be available for use within the main program approximately four seconds after sensing. Testing would be completed to evaluate the computer assisted well control system's response by varying kick size and shut-in surface pressures.

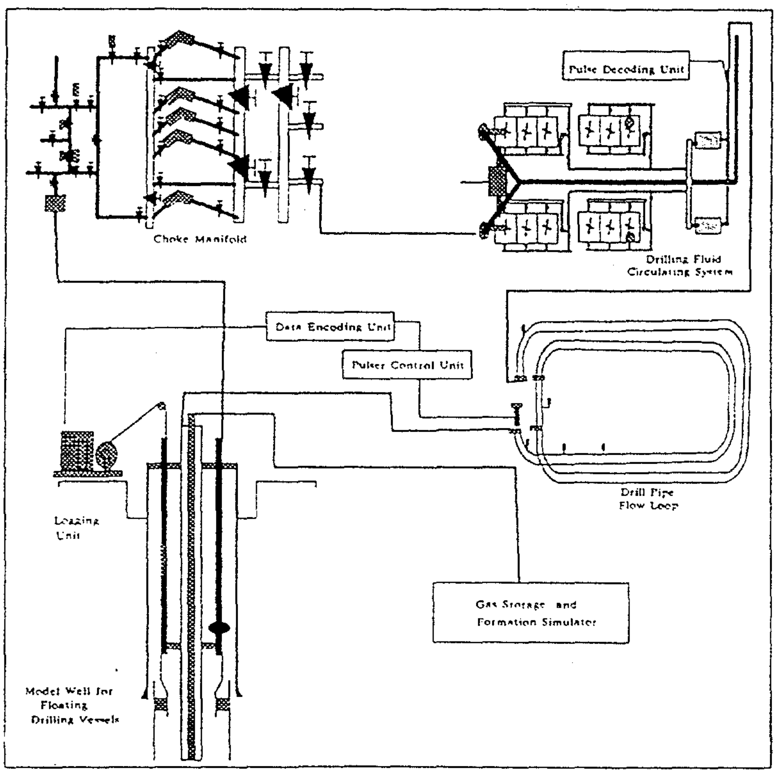

Figure 4 - Computer Assisted Well Control Test Facility

EQUIPMENT AND FACILITY

A large scale simulation of an offshore deep ocean drilling operation was instrumental in the development and testing of the computer assisted well control system. The equipment configuration for this project is shown in Figures 3 and 4, inclusive of a computer, instrumented subsea-configured well, triplex mud pump, mud pulse telemetry system, wire line logging unit, drilling fluid flow loop, reservoir simulator, and high pressure drilling choke. A brief description of the system is as follows.

The mini-computer that provided process control for the system, operated at a clock speed of 4.6 MHz, using only 192k of random-access-memory (RAM) and dual floppy disk drives. The research well, shown in Figure 5, simulates drilling in a water depth of 3,000 feet with 3,000 feet of solids penetration, a true vertical depth of 6,000 feet. Returns are taken from a depth of 3,000 feet by the choke and/or kill line(s), with gas being injected on bottom through a concentric pipe inside the drill string. The well was fully instrumented, facilitating data collection of pertinent parameters such as drill pipe, casing, and kill line pressures; mud pit volume; and fluid flow rate. Electronic sensor errors were within 0.5% full scale, eliminating potential analog signal errors described by Holden and Kelly (1989). For testing, a single triplex mud pump was used along with auxiliary equipment such as centrifugal precharge pumps, mud storage tanks, degassing equipment, and a flare stack to dispose of the spent gas separated from the returning mud stream were also available.

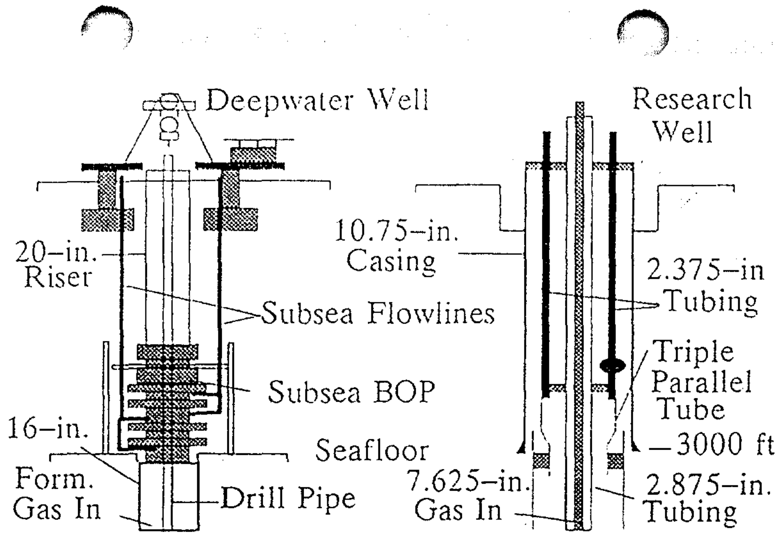

Figure 5 - Subsea Configured Research Well

The mud pulse telemetry system consisted of a BHP sensor, electric line logging unit, encoding computer, drilling fluid flow loop, fluidics design mud pulser, dynamic pressure sensors, and signal decoding computer. Since it was impractical to place a full mud pulse telemetry system on bottom for relaying BHP to the surface, an improvised system was used. In reality the down hole pressure sensor, provided by Geophysical Research Corporation, relayed BHP to the surface computer via an offshore Schlumberger electric line unit. The signal was encoded and pulsed through the 10,000 foot flow loop, received, and then decoded for use in the well control models. The prototype fluidics mud pulser shown in Figure 6, funded earlier by the Mineral Management Service and developed by Harry Diamond Laboratories (Holmes), was used to transmit data in a binary format at frequencies varying from 10 to 12 hertz.

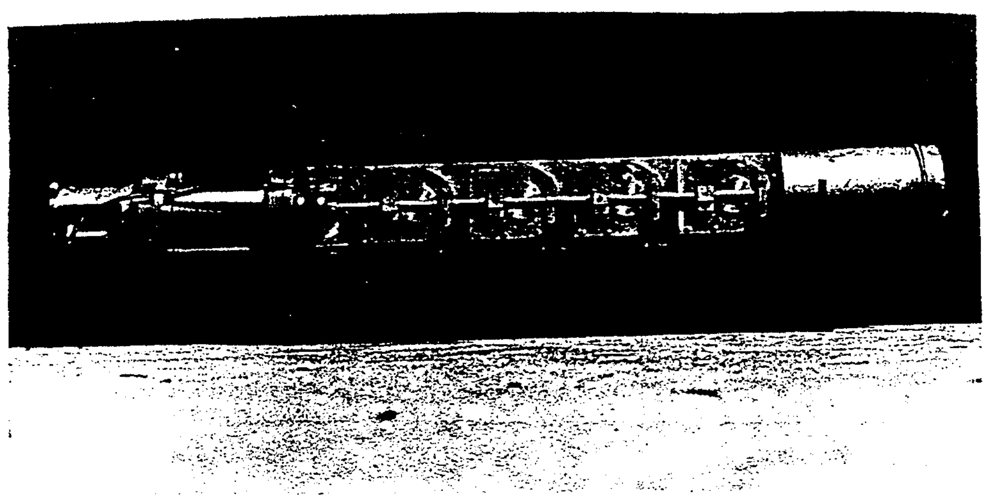

Figure 6 - Fluidics Mud Pulser

Gas kick injection was made possible by a formation reservoir simulator consisting of three 2,000 foot wells capable of storing gas at pressures as high as 4,500 psig. Gas was injected down hole until the desired kick size and shut-in surface pressures were achieved.

Pressure control for the system used an operationally unique high pressure drilling choke. This choke requires only that a hydraulic "set point pressure" be established for proper casing pressure control. As presented by Cain (1987), the floating shuttle/trim element used for controlling the choke fluid flow area is positioned by pressure differentials across the element as shown in Figure 7. Control of the choke by computer was achieved through the A-D-A interface with the use of pneumatic controls to establish both the set point pressure and the choke pump speed. The choice of choke was based on ease of implementation, eliminating the need for an additional software package to control choke element positioning.

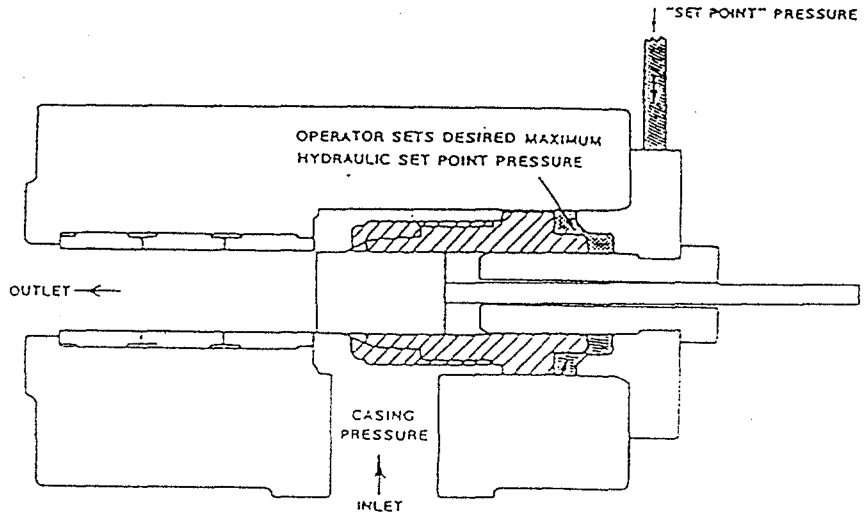

Figure 7 - High Pressure Drilling Choke Design

FINDINGS AND RESULTS

Development of the computer assisted well control system as been completed and successfully tested. The developmental work and testing phase of the project followed the outline prescribed in the "Test Program Design" section of this paper. The results and conclusions will be discussed in a similar format.

Two data bases were established, one containing all the pertinent well specifications, e.g., casing depths, casing sizes, true vertical depth, etc., as found in the daily drillers report and the second containing circulation pressure data obtained from reduced circulation rates taken each tour. Both data files were utilized to complete the necessary computations for a well control kill sheet.

Frictional equations were developed to match the data obtained. As is known, the relationship between pump pressure and flow rates for turbulent flow are logarithmically linear by nature. As stated by Bourgoyne, Millheim, Chenevert, and Young (1986), parasitic pressure losses can be described by the form

$$p = cq^m. \qquad \text{(Eq. 1)}$$

where,
- p - pump pressure, psi
- q - flow rate, gpm
- c - a constant based on mud properties and well bore geometry
- m - slope of line

For subsea well calculations, pump pressure equations were developed for flows through both the riser and the choke. A choke line friction equation was then developed from both data sets and stored for use in the well control model. Hard copies of the friction graphs, friction equations, and kill sheet are then generated for documentation and operator use.

Computer control of the triplex mud pump and choke systems was completed with software developed capable of controlling the entire well kill operation, pump start-up to the flaring of the gas. BHP data has been successfully encoded, transmitted, and decoded in a binary format at a rate of 10 bits-per-second with 100% accuracy and 12 bits-per-second with 95% accuracy. A typical encoding sequence is shown in Figure 8.

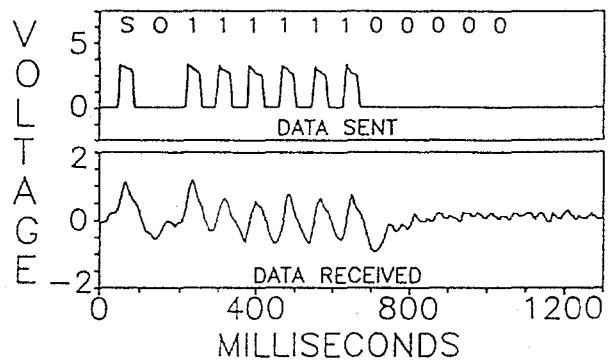

Figure 8 - Typical Fluidics Mud Pulser Encoded Data

As seen in Figure 9, the computer assisted well control system has demonstrated an ability to maintain BHP to ±20 psi while maintaining the pump within ±2 spm. Considering that the initial conditions for this example are almost identical to the manually controlled well exercise shown in Figure 2, the conclusion can be reached that the initial objective of developing improved systems and procedures for reducing the risk of surface and underground blowouts for deep ocean environments has been achieved and demonstrated to be practical. However, implementation to the field will require additional work.

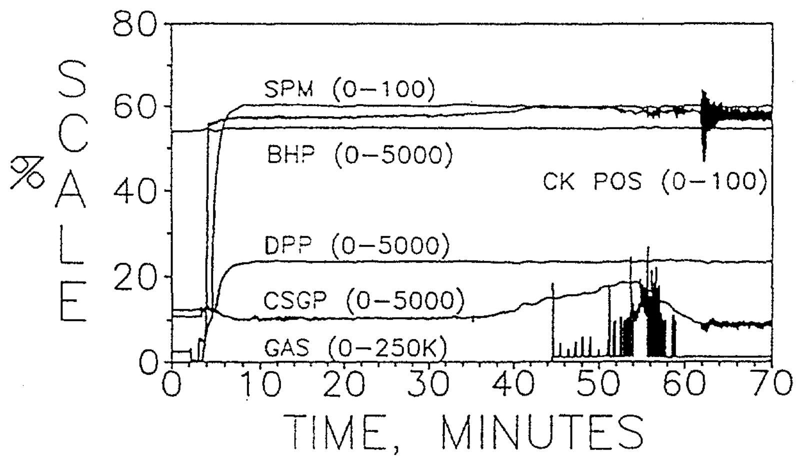

Figure 9 - Computer Assisted Subsea Well Kill Operation

In summary the system was tested by completing 20 separate natural gas kick well kill exercises, varying kick size and shut-in surface pressures. In addition to the gas kicks, in excess of 30 simulated salt water kicks were utilized to refine the developed software. Because of the wells being filled with water during the simulated salt water kicks, rapid pressure responses were recorded, demonstrating the computer models' abilities to respond accordingly. The system for deep ocean well control proved very successful in controlling BHP and the removal of kick fluids from the well bore. Also demonstrated is the reality of being able to incorporate computer assisted measures while drilling technology into a well control safety system that could be implemented in the field.

Portions of this study were presented at the Inernational Well Control Symposium/Workshop, November 27-29, 1989, and at the Louisiana State University MWD Symposium and Exhibit, February 26-27, 1990. Future work will extend this effort to include fixed positioned chokes as well as incorporate trouble shooting expert systems software. Plans are to present all results at an industry conference at a later date.

CONCLUSIONS

1. The application of process control technology to deep ocean well control operations can significantly increase safety through increased BHP control.
2. Fluidics pulser technology as applied to MWD can effectively transmit accurate BHP safety data at rates necessary for use as the controlling parameter in computer-assisted well control safety systems.
3. Mud pulse telemetry systems as applied to well control can provide useful information for the analysis of down hole problems such as washouts and plugged nozzles.
4. Equipment exists that will perform all choke functions on a distributive basis, simplifying the initial design of the well control safety system.
5. Automation of the well control process eliminates the potential for communication errors between the mud pump and choke operators.
6. The automated well control system eliminates the very repetitive and tedious tasks of mud pump and choke control, making the operators available for higher level decisions, resulting in the potential for reduced operator stress.

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REFERENCES

Bourgoyne, A. T., Jr., (January 12, 1982). United States Patents 4,310,050 and 4,310,058.

Bourgoyne, A. T., Jr., Millheim, K. K., Chenevert, M. E., & Young, F. S., Jr. (1986). Applied drilling engineering. SPE textbook series, Vol. 2. Texas: Richardson.

Cain, L. L., (1987). Unique well control choke: design objectives vs. commercial field performance. SPE/IADC Drilling Conference (pp. 713-725). New Orleans: International Association of Drilling Contractors/Society of Petroleum Engineers (SPE), Inc.

Holden, W. R., & Kelly, O. A., (1988, February). Errors inherent in rig measurements of drill pipe and casing pressures. Paper presented at the conference of International Association of Drilling Contractors/Society of Petroleum Engineers (SPE), Inc., Dallas, TX.

Holmes, A. B. The fluidics approach to mud pulser valve design for measurement-while-drilling systems. Unpublished manuscript, Harry Diamond Laboratories, Maryland.

Hughes, V. M., Podio, A. L., & Sepehrnoori, K. (1987). A computer-assisted analysis of trends among gulf coast blowouts. SPE/IADC Drilling Conference (pp. 667-676). New Orleans: International Association of Drilling Contractors/Society of Petroleum Engineers (SPE), Inc.

Kelly, O. A., Bourgoyne, Jr., A. T., & Holden, William R. (1989, November). A computer assisted well control safety system for deep ocean well control. Paper presented at the International Well Control Symposium/Workshop of Louisiana State University Petroleum Engineering, Baton Rouge, LA.