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A Computer Assisted Well Control Safety System for Deep Ocean Well Control

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ABSTRACT

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

The tedious tasks of manually controlling the choke and mud pumps during the well kill operation were automated, allowing the operators to concentrate on higher level decisions. A mud pulse telemetry system was incorporated to relay down hole safety data to the surface, eliminating the necessity of basing all decisions on surface pressures. The software developed will accommodate both surface and subsea rig configurations.

Development and testing of the automated well control safety system was completed at the Louisiana State University Petroleum Engineering Research and Technology Transfer Laboratory. A subsea-configured well simulating 3,000 feet of water and 3,000 feet of sediments as well as a surface configured well with a depth of 6,000 feet were utilized in the testing phase. The system developed was tested with 20 natural gas kicks and in excess of 30 simulated salt water kicks. Results indicate that bottom hole pressure can be maintained to within plus or minus 20 psi in contrast to the plus or minus 200 psi commonly incurred by experienced operators completing manual well control exercises utilizing the same facility. In addition, a reduction in operator stress, enhancing safety, will be achieved as a result of better BHP control and freedom from the repetitive, tedious tasks of pump and choke control.

INTRODUCTION

Today's technology within the oil industry supports exploration for new hydrocarbon reserves further offshore and at increased water depths. To date, wells have been drilled to depths approaching 7,000 feet. Numerous technological problems have been encountered when drilling in this environment and well control solutions have proven to be extremely difficult to achieve and expensive, often requiring specialty muds and sophisticated well plans. However, the increased level of sophistication for drilling operations has not prevented the occurrence of kicks, the unintentional formation fluid entry into the well bore. Loss of control during the well kill operation may lead either to a surface or an underground blowout, with potential loss of life and extensive damage to the rig equipment.

BACKGROUND

Study of well control problems occurring offshore in deep waters revealed three geological facts that make well control for deep water operations much more difficult than for land. These include reduced fracture gradients relative to land rig operations, abnormally pressured formations at shallower depths, and the frequent presence of gas as the formation fluid. This list is not inclusive of all factors affecting well control but includes those most pertinent to this study. A basic understanding of these problem areas is required to better appreciate the need for the system being proposed.

A reduction of formation fracture gradients is commonplace with increasing water depths. Figure 1 demonstrates this by comparing land to subsea drilling operations. All fracture gradients shown are representative for solids penetration depths of 3,500 feet and are expressed as values in units of equivalent pounds-per-gallon (ppge). Note that the ppge fracture gradient reduction associated with increasing water depth does not infer a reduction of total fracture pressure. As the differential between the ppge fracture gradient and the drilling fluid density diminishes, so does the margin for operator error and the size of kick that can be safely removed from the well bore.

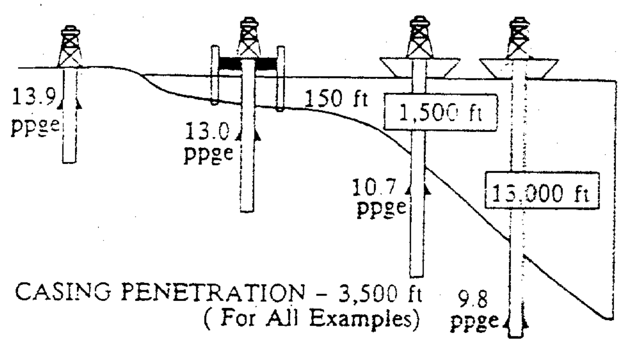

Figure 1 - Deep Ocean Formation Fracture Gradient Comparison

Accentuating the decreased differential between mud weight and the fracture gradient is the presence of abnormally pressured gas zones in deep ocean environments. Figure 2 illustrates a deltaic-type sedimentary environment showing the shale facies upturned in the deeper water, creating possible pressure traps which would extend upward toward the sea floor. Once these pressure traps are penetrated, the well bore is exposed to the higher-than-normal pore pressure gradients.

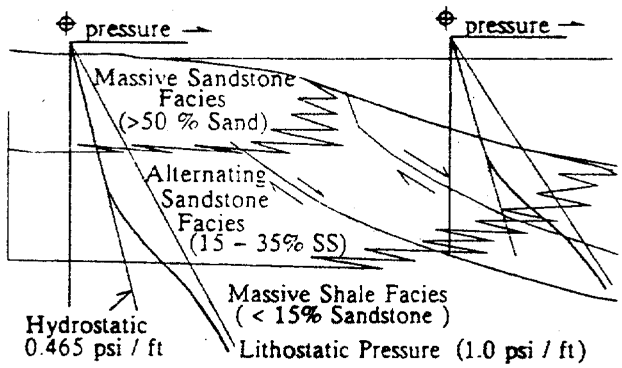

Figure 2 - Shallow Abnormal Pressure

A survey completed by Hughes, Podio, and Sepehrnoori (1987) found that natural gas is the kick fluid in approximately three-fourths of the blowouts that occur in outer continental shelf (OCS) waters in the Gulf of Mexico. As a consequence of low fluid densities, shut-in well head pressures for abnormally pressured, deep water, natural gas kicks are expected to be higher than for kicks composed of salt water or liquid hydrocarbons. When circulating gas kicks to the surface, an increase in the potential for formation fracture due to gas expansion occurs as a result of additional drilling fluid displacement from the well bore. Offseting this additional loss in hydrostatic pressure requires higher surface pressures in order to stabilize bottom hole pressure (BHP).

Protecting against formation fracture, new casing strings are set to protect exposed formations from fracture when the drilling fluid density approaches being equal to the fracture gradient. A typical well plan for deep water offshore operations in the Gulf coast area is shown in Figure 3. As can be seen from the number of casing strings, a given string does not permit much additional footage of new hole to be drilled before setting the next string. Obviously, proper well control is required for safety, but is also an especially important consideration when optimizing the number of casing strings required for a new hole. Better BHP control would allow better utilization of the safety margin obtained through the use of such expensive casing programs.

Once well head pressures have stablized following a kick, the safety of the rig crew and equipment as well as preservation of the well bore then becomes the responsibility of the well control operator. The most commonly used kill procedure, due to its ability to minimize well head pressures, is the weight-and-wait method. However, other methods such as the driller's method and/or a combination of the two are also available to the operators.

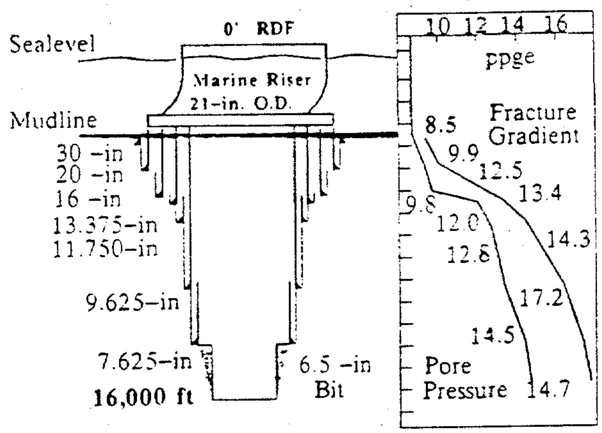

Figure 3 - Typical Deep Ocean Casing Program

Figure 4 is an example of a driller's method well kill operation completed at the Louisiana State University Petroleum Engineering Research and Technology Transfer Laboratory (PERTTL). This well kill operation was a subsea exercise conducted as part of the Minerals Management Service's well control certification class taught at the university. Used in this training exercise is a well simulating 3,000 feet of water and 3,000 feet of solids. A natural gas bubble of approximately eight barrels was injected on bottom. As can readily be seen in the figure, bottom hole pressure varies extensively during the well exercise, approaching plus or minus 200 psi. The largest BHP fluctuations occurred at the beginning of the well kill process. In most real world situations, the gas would not

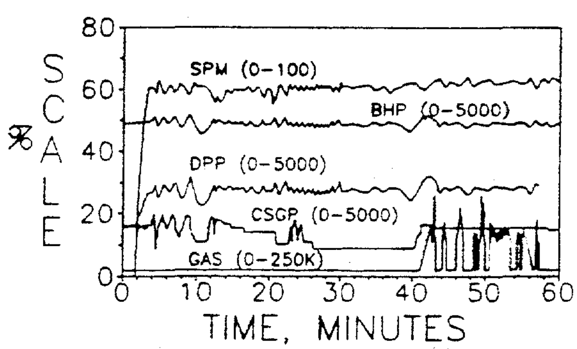

Figure 4 - Manually Controlled Subsea Well Kill

have migrated nor would have been pumped beyond the casing shoe, the weakest formation in the well plan. In this case, increased surface pressure would have exposed the weakest formation at the casing shoe to an excessive and unnecessary equivalent mud weight, risking formation fracture. In addition, pressure drops below the shut-in value would permit additional kicks to enter the well bore, compounding an already difficult situation.

OBJECTIVES

The well exercises at PERTTL have repeatedly shown for several years the inability of experienced operators to consistently hold a constant BHP for the complex well geometry present in deep ocean drilling operations. This fact led to the proposal and the decision to study and make recommendations relative to well control operations in deep ocean waters. Consequently, the expressed objective of this study was to develop improved systems and procedures for reducing the risk of surface and underground blowouts for deep ocean environments. It is believed that completing this objective, improving bottom hole pressure control, increases the safety of rig personnel and equipment alike.

TEST PROGRAM DESIGN

Achieving the stated objective requires evaluation of several well control systems and procedures as well as consideration of human factors associated with manual control. Inconsistency in operator knowledge and expertise for completing a well control procedure has been demonstrated repeatedly in the well control exercises at the university. Inadequate communication between the choke and pump operators plays an obvious role in the oftentimes poor performance in the well kill operation. In addition, numerous operators have difficulty with the many calculations associated with analyzing a well control situation and with the high stress level that may also be present during a real situation. Once the kill procedure is initiated, the operators face several hours of very tedious, stressful work.

The development of a computer-assisted well control procedure for deep ocean environments evolved to eliminate the seemingly repetitiveness of the well control tasks. Two considerations guided the development of the safety system: 1) the ability of the final system to effectively and reliably complete the repetitive tasks associated with well control, and 2) implementation in a form that would be acceptable to the operators.

The developmental plan for the project involved several tasks. Step 1 involved the collecting and storing of data in a form that could be used to complete a kill sheet. Included in this data base were the well parameters from the daily drilling report and the frictional information taken each tour. Step 2 involved the development of a computer program for calculating and outputing a well control plan such that all calculations remain available in the computer and a hard copy is made available to the operator. Step 3 required adapting the triplex mud pump and choke systems for computer control, and developing software to complete a well kill operation. Finally, Step 4, required the development of a switching system that would permit the operator to regain control of the complete system with the flip of a switch. This step, the return to manual control following automated control, is critical especially if unforeseen problems are encountered, and will greatly influence operator acceptance or rejection of the well control procedure.

Upon completion of the system design, both the surface and the subsea wells were utilized in the testing program. Since subsea operations in deep ocean waters is the main thrust of the study, the majority of all work was done on the subsea configured well. Figure 5, showing the surface well, represents the conceptualization of the test system in final form.

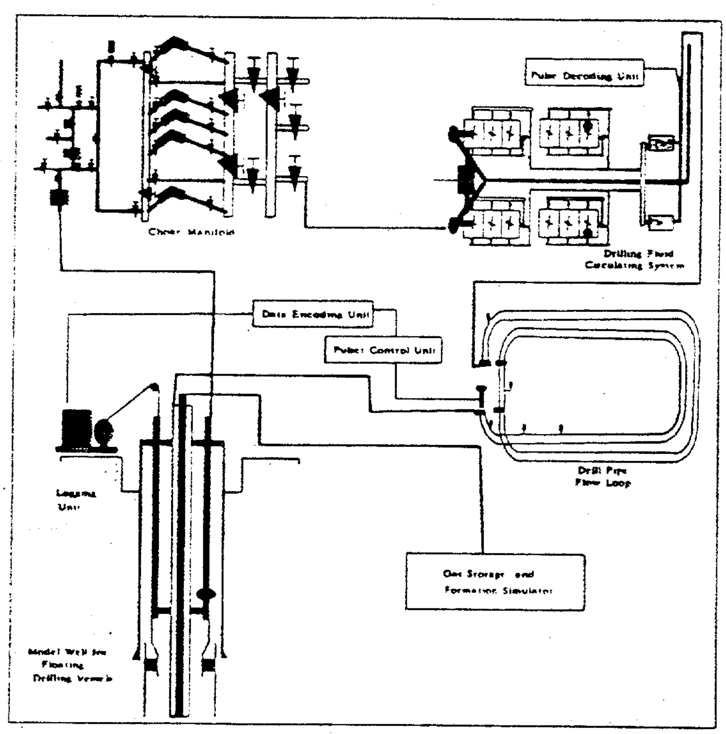

Figure 5 - Computer-Assisted Well-Control Test Facility

As seen in the figure, the pumping system pumps drilling fluids through the flow loop and down the well bore, which returns through the choke system to the mud pits. A gas storage formation simulator was available to inject gas kicks at 6,000 feet. Located on the bottom of the hole was a pressure sensor for collecting true BHP data. These data were available for use in the well control software after being encoded, pulsed, and decoded. In the procedure described, bottom hole pressure data were made available for use within the main program approximately four seconds after the sensing. Tests were completed with varying kick size and varying surface shut-in pressures, evaluating the automated well control system's response.

TEST FACILITY AND EQUIPMENT

A large scale simulation of an offshore deep ocean drilling operation was instrumental in the development and testing of the automated well control safety system. The equipment configuration for the project is shown in Figure 5 and includes:

1. Computer,
2. Subsea-configured well,
3. Triplex mud pump,
4. Drilling fluid flow loop,
5. Mud pulse telemetry system,
6. Instrumentation,
7. Reservoir simulator,
8. High pressure drilling choke, and
9. Wire line system.

A brief discussion of each item follows.

1. Computer

A mini-computer with an analog-to-digital-to-analog (A-D-A) board installed provided process control for the system being developed at a clock speed of 4.6 MHz. The computer is a desk top model containing dual floppy disk drives and 192k of random-access-memory (RAM) storage space. The A-D-A board has a capacity for 8 inputs and 8 outputs.

2. Subsea Configured Well

A sketch of the research well utilized for testing the automated well control safety system, exclusive of the mud pulse telemetry system, is shown in Figure 6. When comparing the research well to the typical deep water well also shown, the similarity is obvious. Physically the research well simulates drilling in a water depth of 3,000 feet with

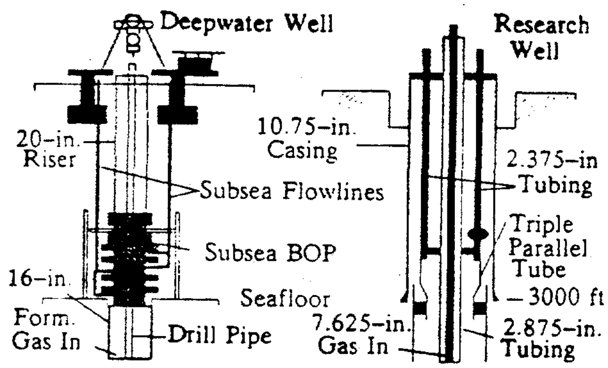

Figure 6 - Subsea Configured Research Well

3,000 feet of solids penetration, making the total true vertical depth equal to 6,000 feet. Returns are taken from a depth of 3,000 feet by either the choke or kill line. The gas injection line is concentric with the drill string, accommodating the injection of natural gas kicks on bottom. The well is fully instrumented, facilitating data collection of pertinent parameters such as drill pipe, casing, and kill line pressures, mud pit volume, and fluid flow rate.

3. Triplex Mud Pump

Two triplex mud pumps served as the drilling fluid prime movers. A single pump was used on this project and has a pumping capacity of 1.3 gallons-per-stroke. Normally, for a pump-out kill procedure, the pump is operated at a reduced circulation rate of 60 strokes-per-minute. Support for the triplex mud pumping system consisted of a centrifugal precharge pump, 180 barrel mud storage tanks, full degassing equipment, and a flare stack to dispose of spent gas separated from the mud stream.

4. Flow Loop

The flow loop was used in conjunction with the fluidics mud pulser to transmit BHP data 10,000 feet in the well control system. The loop, as shown in Figure 5, was made of 4 1/2 inch, 20 pounds-per-foot drill pipe. Pressure taps were located at the pulser and then at 25, 250, 500, 5,000, and 10,000 feet upstream. All of the drill pipe were screwed together except for the 8 bends, 37 foot radii, which were welded.

5. Mud Pulse Telemetry System

The mud pulser operated on a fluidics principle and was a prototype funded by the Mineral Management Service and developed by Harry Diamond Laboratories (Holmes). The pulser unit disturbed the fluid flow, changing radial flow as it passed through the pulser to vortex flow, slowing down the fluid and creating a positive pressure pulse. Data were transmitted in a binary form at a frequency rate of 10 and 12 hertz, a minimum of four times faster than is currently found in the field. Pressure pulse amplitude was controlled by varying the number of active flow chambers on the pulser, adjusting to varying flow rates. Flow rates used for testing required two flow chambers, creating pressure pulses of up to 200 psi at the tool and varying 25 to 50 psi at the sensor, 10,000 feet upstream. The pulser has a total of four flow chambers as shown in Figure 7.

Figure 7 - Fluidics Mud Pulser

6. Instrumentation

All pressure sensors used were analog devices operating on either current or voltage signals. When appropriate, sensors were located directly at the source of the parameter being measured, eliminating the potential errors of precharge overpressure and of pressure dead bands described by Holden and Kelly (1988). Accuracy of the sensors was a minimum of 0.5 percent full scale, making control much more reliable and precise than if using hydraulic analog gauges.

7. Reservoir Simulator

Injection of gas kicks at a depth of 6,000 feet in the test wells was made possible by a formation simulator consisting of three wells fully cased with cement plugs on bottom. Illustrated in Figure 5, these 2,000 foot simulator wells were identical, having 7 inch, 38 pounds-per-foot casing with a 2 3/8 inch tubing string hung from the well head. The wells were used in gas compression by flowing pipe line gas into the annular space and then closing off the annulus. Fluid was then pumped down the tubing string, compressing the trapped gas in the annulus to pressures as high as 4,500 psig. Once the gas was compressed creating a volume sufficient for injection into the well bore, valves were opened allowing the high pressured gas to flow through the gas injection line in the subsea well to a depth of 6,000 feet. Gas flow into the well continued until the desired kick size and shut-in surface pressures were achieved. At that point the reservoir simulator was either closed-in, leaving one kick in the test well, or left open to generate additional kicks when bottom hole pressure was not properly maintained.

8. High Pressure Drilling Choke

Pressure control for the automated well control system required the use of a high pressure drilling choke. An operationally unique choke was selected, requiring 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 was positioned by pressure differentials across the element, Figure 8 demonstrates this process. Since the shuttle/trim

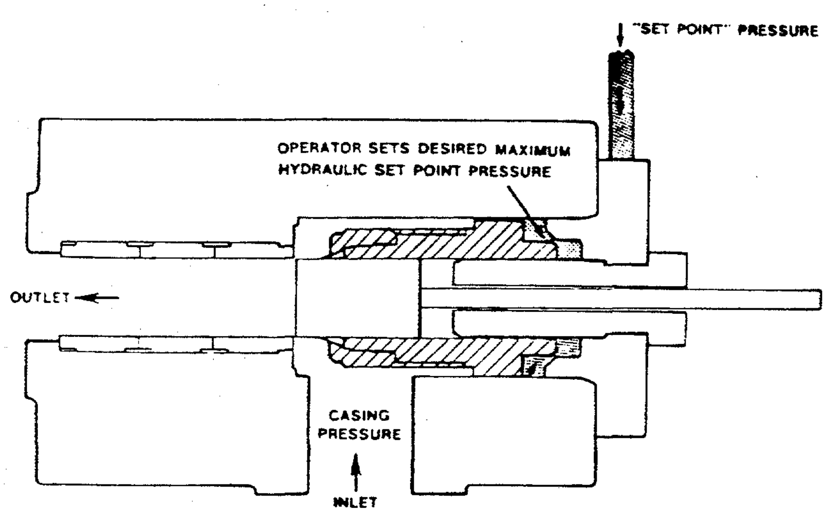

Figure 8 - High Pressure Drilling Choke Design

element end surface areas were identical, the casing pressure was automatically obtained through free element movement to a position that created a casing pressure equal to the hydraulic set point pressure. As an example, if during operations the casing pressure dropped, the set point pressure overbalance would move the shuttle/trim element toward the closed position until the casing pressure stabilized equal to the set point pressure. The reverse would be true should a pressure increase be incurred in the casing, causing the choke to automatically open. Choke specifications indicate that the shuttle/trim would respond to differential pressure as low as 3 psi.

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. Set point pressure is linearly controlled with a 3 to 15 psi pneumatic signal while the air flow rate that adjusts the pump speed is achieved by use of a 3 to 15 psi pneumatically controlled flow control valve. Once the mechanical interface was completed, the choke could then be effectively used as a distributive type function, leaving the mini-computer available for other tasks.

The choice of choke was based on ease of implementation, i.e. an additional software package for pressure control by the choke was not required. With additional software development, other choke designs could have been used in the automation process.

9. Wire Line System

Implementing the final testing phase of the well control safety system required evaluating the mud pulse telemetry system and documenting its effectiveness in relaying safety-related data to the surface for use. Since costs prohibited placing the pulser at the end of the tubing string in the well bore, the decision was made to simulate down hole pulsing by pulsing the safety related data through the 10,000 foot flow loop. The wire line unit was used to place a pressure tool at the bottom of the surface configured well. This well was selected for use since the subsea configured well was not physically able to accommodate the tool. The pressure readings were sent to the wire line unit on the surface by way of an electric line. Instrumentation within the wire line unit converted the BHP signals, passing them along to the encoding unit for pulsing in the flow loop. All data transfers, including pulsing time, were accomplished in less than 4 seconds which is sufficient for use as the controlling parameter.

FINDINGS AND RESULTS

Development of the computer assisted well control safety system for deep ocean well control has 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.

Step 1 was accomplished with the development of two data bases. One file contains all the pertinent well specifications, e.g., casing depths, casing sizes, true vertical depth, etc., as found in the daily drillers report while the second contains circulation pressure data obtained from reduced circulation rates taken each tour. Both data files are required to complete computations for the well control kill sheets.

Setting up the first data file was straight-forward, but the frictional data file required the development of frictional equations. Since the relationship between pump pressure and flow rates for turbulent flow are logarithmically linear by nature, software was developed to collect the required data and provide the necessary curve fits. Bourgoyne, Millheim, Chenevert, and Young (1986) state that parasitic pressure losses are in the form of

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

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

In the case of a subsea well, pump pressure equations are developed for flowing through the riser and also through the choke. One additional equation was derived utilizing both the riser and choke circulating pressure data, the curve-fit equation for choke line friction. Figure 9 shows a copy of a printout as generated by the software, displaying the data graphically and in the form of equations.

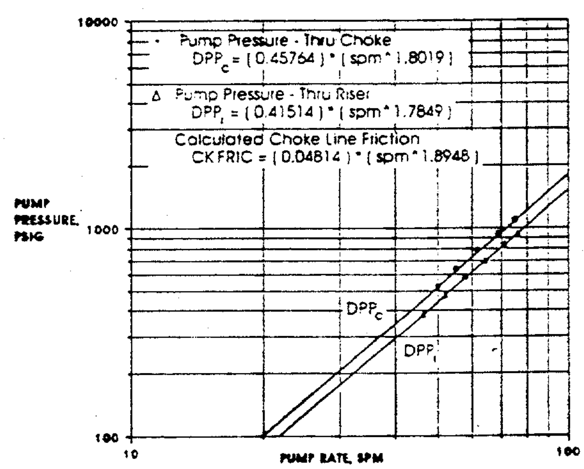

Figure 9 - Typical Subsea Pump Flow Rate vs. Pump Pressure Curve Fit

Step 2 of the "Test Program Design" was fulfilled by the development of software to complete a well kill sheet. The data stored in the two previous files were accessed, and a complete well control plan calculated. This data was stored for later use by the automated well control safety system with a hard copy printed, providing the operator with all the information necessary to complete a manual well kill operation.

Step 3 required the automation of the triplex mud pump and choke systems along with the software for controlling these systems throughout the entire well kill operation, pump start-up to the flaring of the gas. The software developed can control the pump to within 2 strokes-per-minute, making pressure control much easier. Also, the automated choke control permitted maintenance of pressure control by computer within the design specifications of the choke.

Completing the data loop as used in the automated well control system was the pulsed BHP data. This data was transmitted in a binary format at a rate of 10 bits-per-second with 100% accuracy and 12 bits-per-second with 95% accuracy, words contained 12 bits. A typical encoding sequence is shown in Figure 10. As can be seen, even at a data transmission rate of 12 bits-per-second, the pulse amplitude greatly exceeds the pump noise.

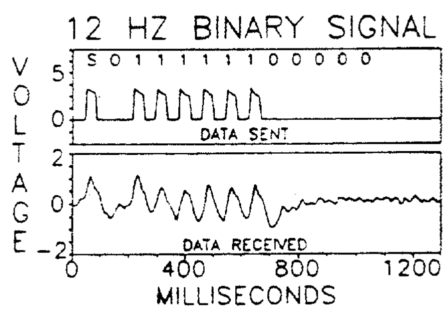

Figure 10 - Typical Fluidics Mud Pulser Encoded Data

When all the data and the software developed were merged into the desired computer-assisted well-control safety system, a system had been developed that could calculate all needed well kill plans and complete the kill operation from the time of stabilized shut-in pressures to the end. Figure 11 demonstrates the interaction of all the components developed while Figure 12 demonstrates the level of control obtained. As can be seen in Figure 12, bottom hole pressure control was maintained to plus or minus

20 psi while the pump rate was maintained to a deviation of less than 2 strokes-per-minute. Considering that the initial conditions of this example are almost identical to the manually controlled well exercise in Figure 4, the conclusion can be reached that the initial objective of improved bottom hole pressure control has been obtained, resulting in improved systems and procedures for reducing risk of surface and underground blowouts in deep ocean environments.

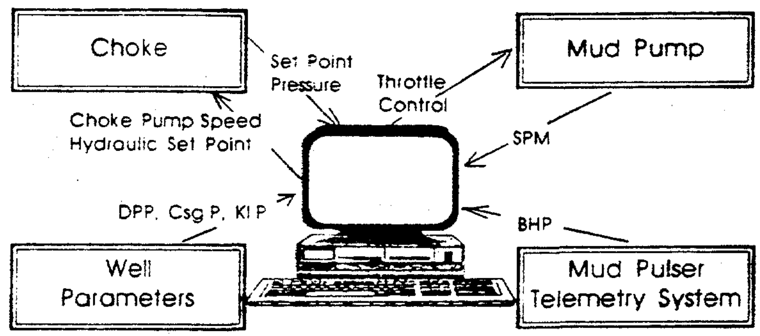

Figure 11 - Computer Control for Automated Well Control Safety System

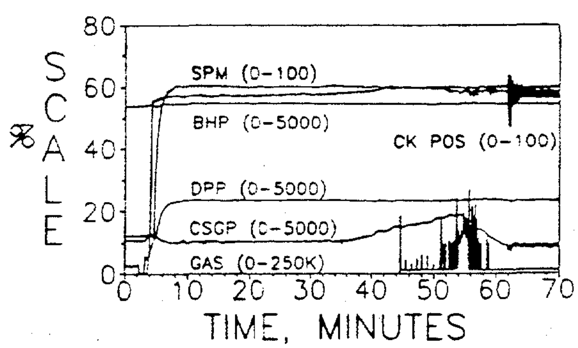

Figure 12 - Automated Well Kill Operation

Testing of the system was completed utilizing the subsea configured well by injecting 20 separate natural gas kicks at a depth of 6,000 feet. Kick size was varied as was the shut-in surface pressures. In addition to the gas kicks, in excess of 30 simulated salt water kicks were completed. The simulated salt water kicks were used in the initial testing phase for safety and later used to refine the developed software. As a consequence of the wells being filled with water, pressures responded quickly, requiring that rapid response models be developed.

In concluding this project, several items were developed that could be readily implemented in the oilfield. The system for deep ocean well control proved very successful by controlling bottom hole pressure to plus or minus 20 psi when it had been demonstrated that experienced operators vary bottom hole pressure as much as 200 psi on the same facility. This automated system can easily be implemented for the field in total or in part. Individual software packages could be very useful and utilized in daily operations, e.g. the frictional package could be used each tour to generate frictional information whether surface or subsea operations are in progress. Secondly, the well kill program could be implemented as a routine training package for well control operations.

CONCLUSIONS

1. The application of process control technology to deep ocean well control operations can significantly reduce the variations in bottom hole pressure while completing a well kill operation.

2. Better bottom hole pressure control by the computer-assisted deep ocean well control safety system reduces the risk of surface and underground blowouts, and results in improved safety for rig personnel and equipment.

3. Fluidics pulser technology as applied to mud pulse telemetry can effectively transmit to the surface safety data, e.g. bottom hole pressure, at rates acceptable for use as the controlling input for computer-assisted well control safety systems.

4. Computer-assisted well control safety systems for deep ocean well control can be designed user-friendly, making the systems more readily accepted in the field.

6. Equipment exists that will perform all choke functions on a distributive basis, simplifying the initial design of the well control safety system.

7. Automation of the well control process eliminates the potential for communication errors between the mud pump and choke operators.

8. 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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