AN EXPERIMENTAL STUDY OF BULLHEADING OPERATIONS FOR CONTROL OF UNDERGROUND BLOWOUTS

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Executive Summary

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Underground flows have been a contributing factor to about one-fourth of the surface blowouts that occurred on the OCS during the last two decades. Underground flows that reach the surface have been a serious problem in some deep-water areas of the Gulf of Mexico and could be a significant hazard to the very expensive production facilities needed to exploit reservoirs found in deep water. Well-control operations are much more difficult when underground flows are in progress, and often the well remains under pressure for long periods of time. This increases the risk of personnel errors that could result in large volumes of hydrocarbons being brought to the surface.

The design of a well kill for an underground blowout is often more by trial and error than through use of a standard calculation procedure. Existing well control simulators and computer models of well control operations are not available that can accurately model countercurrent gas migration during bullheading operations. It has been difficult to develop good well-control training modules in the area of underground blowouts because a systematic approach has not yet been defined. In some cases involving underground blowouts, the problem may never be fully resolved, and an underground flow may continue after the well is abandoned. Such situations are often difficult to detect until another well is drilled at a later time that finds pressure unexpectedly at a more shallow depth. Significant loss of natural resources as well as potential environmental damage can result from undetected underground flows that continue for long periods of time.

An experimental study to investigate the bullhead method of well control was performed. The primary focus of the investigation was the downward displacement of gas by liquid, which requires consideration of counter-current flow behavior. Experiments were conducted in a full-scale well, using a computer-controlled down-hole fracture simulation system; water and low-viscosity drilling mud were used for bullhead fluids. Experiments were also conducted in an inclined flow loop so that the effect of vertical deviation angle could be investigated. The results from these experiments were used to calibrate a new computer model for bullheading operations conducted to kill an underground blowout.

Chapter

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Introduction

The objective of this research was to investigate the gas removal efficiency for the bullhead method, with the goal of identifying the key factors involved and determining a predictive-method that could be incorporated into a computer model for bullheading operations conducted to kill an underground blowout.

In drilling for natural resources, the operator may encounter a variety of permeable zones containing oil, gas, and/or water at varying pressures. One common goal in designing the well and conducting drilling operations is to maintain the pressure in the well bore at values equal to or greater than the adjacent formation pressures. This pressure maintenance prevents a "kick" or "influx," which is the undesired flow of formation fluids into the well bore. Once a kick has entered the well bore, well control techniques are used to regain control of the well; prevent further influx; remove the influx from the well; and increase the density of the drilling fluid in the well as needed.

The most commonly used well control techniques utilize a controlled well bore circulation, as shown in **Figure 2.1**. The operator pumps mud down the drill string while controlling the well bore pressures by using a choke at the outlet. The operator continues to pump mud and operate the choke until the influx has been removed from the well and the density of the drilling fluid is such that the static column of fluid will prevent further influx when there is atmospheric pressure at the top of the mud column.

There are several variations of the circulation method, the most common of which are the driller's method and the wait-and-weight method. In the driller's method, the current mud density (that in the well bore) is used to circulate out the kick. After all influx has been removed from the well, further circulation is needed to increase the fluid density. In the wait-and-weight method, the "kill mud weight," which is the required mud density to statically control the well, is calculated. The density of the drilling fluid is increased to the kill mud weight and is then circulated into the well. After the kick has been circulated out, no further circulation is required. These circulation methods are generally considered to be safe and efficient well control techniques. However, in some situations, these methods are neither applicable nor desirable. Examples of these situations include:

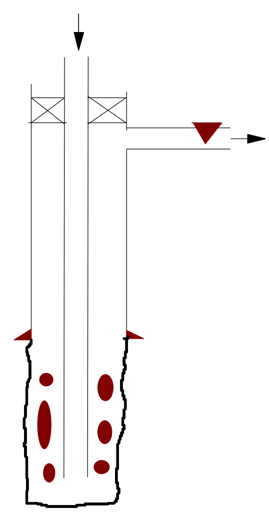

Figure 2.1: Circulation method.

1. The circulation of the well is disabled due to a plugged drill string or bit;

2. The operator does not want to handle hazardous kick fluids, such as hydrogen sulfide, at the surface;
3. The operator does not want to handle large volumes of kick fluids, typically gas, at the surface for a complex situations such as deepwater drilling operations;
4. An underground blowout is in progress; or
5. The well needs to be killed prior to work-over or well abandonment operations.

The bullhead method is considered to be an alternative in many of these situations. When "bullheading," the operator forces mud into the well from the surface, intentionally causing a subsurface fracture, as shown in **Figure 2.2**. If the method is successful, all of the influx is forced out into the fracture and the fracture closes after bullheading is stopped.

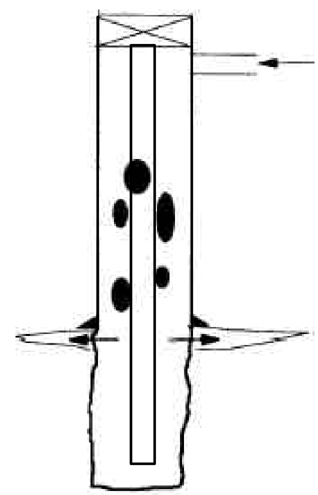

Figure 2.2: Bullhead method.

Bullhead attempts are currently performed in the field by a trial-and-error approach, as a suitable design method is not available. For a given well situation and an assumed kill fluid and pump rate, prediction of both the efficiency of removal of influx and the maximum pumping pressure is desirable.

The primary complication in modeling bullheading attempts is the possibility of counter-current flow. While the mud is pumped downward, the gas has a tendency to flow upward due to the density difference between gas and mud. Most research on two-phase flow has focused on co-current flow and has not often addressed counter-current flow.

The bullheading technique used in the research well was to inject mud at a constant rate. Prior to injection, the gas in the well was at the top of the wellbore as a continuous slug. This study includes an investigation of the effect of mud properties; mud injection rate, in terms of average annular velocity; fracture gradient; and initial amount and height of gas. Wellbore geometry and fracture depth, which may also be significant, were held constant during this research. The research well experiments were supplemented with experiments conducted in an inclined flow loop to determine the effect of vertical deviation angle. The experimental program is described in more detail in the next chapter.

Chapter
3

EXPERIMENTAL PROGRAM

In order to calibrate a computer model for bullheading operations to kill an underground blowout, experimental data was needed on countercurrent gas migration in long annuli containing non-Newtonian fluids. No known prior work had been published in this area.

The experimental research was conducted in a 2000 ft research well that was configured to allow formation fracture to be simulated. In addition, experiments were conducted in a 45 ft inclined flow loop to determine the effect of a large vertical deviation angle on countercurrent gas slip velocity. This chapter describes both the experimental program conducted in the 2000 ft well and the experimental program conducted in the 45 ft inclined flow loop.

Research Well Experiments

For the initial study of bullheading, the following components were used:

- a full-scale cased well capable of high pressure (up to 3,000 psi);
- a mud system capable of treating, pumping, de-gassing and storing water-base fluids;
- a pressurized storage well to supply natural gas for simulating the kick fluid;
- a down-hole fracture system capable of emulating formation fracture and losses;
- a pump rate control system; and
- a data collection and control system.

The first three items were available at the LSU Petroleum Engineering Research and Technology Transfer Laboratory (PERTTL). Of the last three, the formation fracture system had not been created before, so further work was needed to define its functional requirements.

For the purposes of this research, the down-hole fracture phenomenon had to exhibit two key aspects: The fracture had to open whenever well bore pressure exceeded the specified fracture pressure, and the well-bore fluids had to be removed from the well bore at the fracture depth. A variety of well designs and fracture simulation methods were considered. The selected design consisted of these components:

- A well design with a flow path to the surface reserved for fluids from the fracture;
- Continuous bottom-hole pressure monitoring;
- Real-time pressure control and flow out of the simulated fracture using a surface choke with computer control.

This design allowed one computer system to be built that encompassed both data collection and logic for the fracture and pump controllers. This system, called the Live-well System, was designed for use in this research and for future use in training and other research projects.

One of the existing gas storage wells at PERTTL was selected for use; the surface piping was modified for this research, but no other changes to the well were required. A schematic of the research well is shown in **Figure 3.1**, with the simulated well design shown in **Figure 3.2**. For this experiment, only the portion of the well above the fracture was of interest. Thus, the well bore pressure opposite the fracture is the same as the bottom-hole pressure in these experiments.[1]

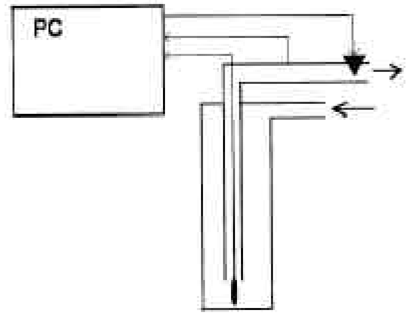

Figure 3.1: Configuration of research well.

The well is cased with 7-in., 38-lb/ft casing (inner diameter of 5.92 in., and annular capacity of 0.0286 bbl/ft) to a depth of 1,994 ft. A string of 2 3/8-in., 4.7-lb/ft tubing (capacity of 0.00548 bbl/ft) extends to 1,903 ft. Pump input via a 4-in. line enters at the top of the annulus. The tubing output is routed to a MI SWACO automatic choke via a 4-in. return line. A down-hole pressure-sensing tool is suspended on a wire line in the well. Gas is introduced into the annulus of the well via a line at the surface.

An analog/digital data collection and control system was installed using a personal computer. The input signals measured were pump pressure, choke manifold pressure, bottom-hole pressure, and pump rate. All of these sensors, except the one for the bottom-hole pressure, generate 4-20 milliamp current signals. The bottom-hole pressure sensor produced an 11-14 KHz signal that was converted to 4-20 milliamps. Two output signals were used to control the automatic choke set-point pressure and the mud pump rate. Both of these were 4-20 milliamp control signals.

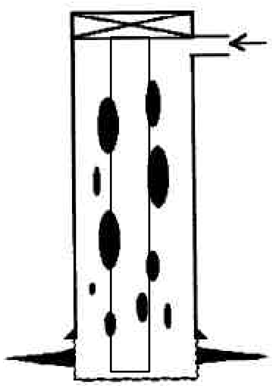

Figure 3.2: Simulated well design and bullhead situation.

The combination of well bore geometry and the computer data collection/control system allowed the tubing string to simulate a subsurface fracture effectively. This was done by continually sensing the bottom-hole pressure and the choke manifold pressure and calculating the optimum choke pressure setting for the desired fracture pressure. This resulted in the "fracture" being closed when bottom-hole pressure was below fracture pressure and "opening" (allowing flow out) when bottom-hole pressure reached fracture pressure. Since the gas was less dense than the fluids used, once gas and/or liquids from the well bore entered the tubing string, they were permanently removed from the annulus, as would be the case if the gas had entered a formation fracture.

A commercially available choke was used in this research. This choke's design is based on the "balanced piston" principle, whereby the operator (computer or human) sets a pressure level behind a

[1] This would not be true in a typical field situation, but it was not necessary to model the interval below the fracture because no countercurrent flow would be present in this interval.

floating piston, which hydraulically balances against the pressure upstream of the choke assembly. This design is more adaptable to computer control, as opposed to choke designs where the operator controls the choke performance by setting an orifice position. In addition to emulating fracture pressure, the fracture logic was required to position the choke in the optimum position for fastest response, with the choke being closer to opening as the fracture pressure was approached. The fracture control logic was developed by separately considering the cases of the fracture being open or closed.

When the bottom-hole pressure is below fracture pressure (i.e., the fracture is closed), the optimum choke setting is specified by:

$$P_{CKSETP} = P_{CKMAN} + (P_{FRAC} - P_{BH}) \tag{2.1}$$

This logic keeps the choke closed by the pressure differential of bottom-hole pressure below fracture pressure (providing effective sealing performance) and results in the choke being on the verge of opening as fracture pressure is approached (providing quick fracture action).

The simulated fracture has been defined as a simple model whereby the fracture will open as needed to maintain well bore pressure opposite the fracture (which was equal to bottom-hole pressure in the experimental well) at fracture pressure when the fracture is opened. Ideally the fracture will operate so as to prevent well bore pressure opposite the fracture from exceeding fracture pressure. While this is a simple model, it is sufficiently representative for the primary purpose of studying fluid (gas and liquid) behavior in the annulus during the bullhead process. To meet the well bore pressure condition specified, the choke must reduce the well bore pressure in the event that it exceeds the fracture pressure. This adjustment must also be optimized for efficient and accurate choke positioning. For the case of well bore pressure equal to or greater than fracture pressure, the optimum choke setting is specified by:

$$P_{CKSETP} = P_{CKMAN} - (P_{BH} - P_{FRAC}) \tag{2.2}$$

In the event that the well bore pressure exceeds the fracture pressure, this setting reduces it by the correct amount, while maintaining flow through the fracture.

Equations 2.1 and 2.2 cover both cases for the fracture, closed and open, and cover all possible bottom-hole pressures. Each of these equations is equivalent to:

$$P_{CKSETP} = P_{CKMAN} + P_{FRAC} - P_{PH} \tag{2.3}$$

Thus only one equation for is needed choke control and choke control does not require knowledge of the fracture state versus time, pressure, or fracture history. An additional benefit of this relationship is that it is computationally efficient and can be used in real time on current personal computers. Equation 2.3 was used to provide the control logic used for the formation fracture simulator in this research.

To operate the fracture in real time, during each time step the personal computer sensed the bottom-hole and choke manifold pressures, calculated the required choke set-point pressure, and set the output current to position the choke at the desired set-point pressure. A relationship was developed between control current and corresponding choke performance. This relationship was developed directly and dynamically by sending fixed levels of current to the choke and observing the resulting choke manifold pressure once the flow system had reached equilibrium. The pump rates were varied in these experiments, and the resulting relationship between level of control current and choke pressure was found to be linear and independent of pump rate—over a wide range of pump rates. This direct-control relationship for choke control can be defined as:

$$I_{CKSETP} = K_0 + K_1 P_{CKSETP} \tag{2.4}$$

Computer control of pump rate had been accomplished before for automated well control research at the LSU research facility. However, the control of the pump rate in this research proved to be more challenging to develop. In comparison with previous research, the pump controller was subject to more severe loading demands on the pump and more rapid changes in pump discharge pressure. For the first attempt, the direct-control approach was tried and quickly proved to be unsatisfactory in this application. The complicating factors that appeared included a time lag between change in control current and pump response; a large amount of inertia in the pumping system; and unwanted interaction between the pump rate and the pump discharge pressure. A proportional controller with a feedback loop was developed for the pump control. In each time step, the controller sensed the pump rate, calculated the change in control current based on the needed change in pump rate, and adjusted the control current by the calculated change. The equation for the change in control current was:

$$\Delta IQP = \frac{(q_{P,TARGET} - q_{P,MEAS})}{K} \tag{2.5}$$

In initial testing, the control factor K was held constant, as is typical for proportional controllers. While this controller performed better than the previous, its performance was not acceptable over the expected range of pump rates and under rapidly varying discharge pressures. In particular, the controller tended to respond sluggishly when large rate changes were needed and to overshoot when small changes were needed. Further tuning was attempted to try to rectify these two situations; however, improving one would always worsen the other. The control logic was modified so that the constant factor K was replaced by the following function:

$$K = f\left(\left|q_{P,TARGET} - q_{P,MEAS}\right|\right) \tag{2.6}$$

The control program allowed the operator to modify the values and shape of the function for K. Test running the pump at different rates and pressures with linearly varying functions for K significantly improved pump control performance. However, it was found that due to the inertia of the pump system, it was wise to limit the value of K for extreme changes in pump rate. These observations resulted in the functional shape for K shown in **Figure 3.3**. The control procedure implemented in the Live-well program provides recommended values for the control function but allows the operator to change these if needed.

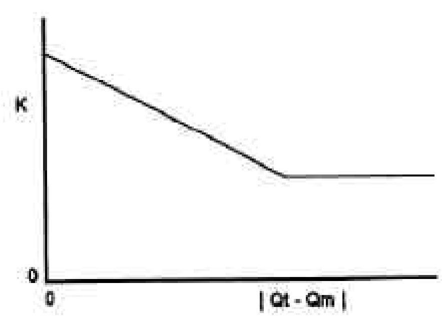

Figure 3.3: Functional Shape of Pump Rate Control "Constant"

General Live-well Procedure

The primary purpose of the Live-well experiments was to evaluate the effect of the main factors—influx removal rate and pump pressure—on the efficiency of the bullhead procedure. Efficiency was defined as the amount of gas removed from the annulus by the bullhead procedure. This removal efficiency was defined by:

$$R = \frac{V_{i,SC} - V_{f,SC}}{V_{i,SC}} \tag{2.7}$$

The basic steps followed in the experimentation were:

1. Ensure that fluid is uniform throughout well.
2. Place gas at top of annulus as a continuous slug.
3. Start fracture simulator at desired fracture pressure.
4. Start pumping down annulus at desired rate.
5. Monitor flow of liquid and gas out of fracture. Continue until gas removal ceases and system has stabilized.
6. Stop pumping and shut in well.
7. Measure amount of gas remaining in well.

Live-well Experimental Design

Maximizing the ranges over which the data were collected, such as fracture pressures used, was desirable to focus as much as possible on the removal efficiency of bullheading and to minimize the effects of experimental error. This was especially important in the full-scale well tests, where conducting the experiments and measuring the results are typically more difficult than in testing conducted in a laboratory.

For a given experiment, the formation fracture system needed to be capable of providing the desired fracture pressure throughout the full bullhead sequence. In general, the sequence followed was:

1. Fracture is closed at start and gas is at top of annulus.
2. As mud is injected, it compresses gas and bottom-hole pressure rises.
3. Fracture opens and flow starts up fracture exit string.
4. Fracture opens and closes as dictated by actual well conditions. This continues until equilibrium condition has been reached.
5. Pump is stopped and well is shut in.
6. During the flow period, the tubing may be filled with mud, gas, or a combination of the two, under various pressures.

Based on simple hydraulics analysis of the experimental procedure, the minimum bottom-hole pressure was expected to occur if the tubing string were completely displaced by gas. Also the maximum pressure was expected to occur while pumping at the injection rate with the tubing full of mud, incurring the full mud column hydrostatic and friction pressures. Of the two cases, the maximum bottom-hole pressure was a primary concern because the fracture was in effect controlled by a choke at the surface. With the choke open, the hydrostatic and friction pressures in the tubing string would limit the fracture pressure available at a given pump rate.

The initial tests were conducted in two stages: water and natural gas with no fracture control; then water and natural gas with fracture control. The first stage was used to test the system integrity and the pump controller. The surface gas removal and flaring were adequate to handle the gas volumes generated in the experiment. Without the fracture control, large slugs of gas would exit, resulting in bottom-hole pressure drops and more gas slugs. This seemed to represent the most severe gas-handling situation.

With the addition of fracture control in the second stage of tests, the system worked much more smoothly. Overall, the performance of the controllers was acceptable—the fracture controller kept bottom-hole pressure within 50 psi of the target value, and the pump controller kept the pump rate within one stroke per minute of the target rate.

Ideally, for each pump rate used in the experiment, the pump rates should span from no gas removal to complete removal. Results of initial runs with water and gas were combined with friction calculations for viscous mud to arrive at the following test matrix:

- Fluids: water, low-viscosity mud.
- Formation fracture pressures: 2000, 3000 psi.
- Pump rates: 12.50, 18.75, 25.00, 37.50, 50.00 gal/min.

Measuring the gas required:

1. First ensuring that gas was at the top of the annulus and in a continuous slug with liquid below.
2. The bottom-hole and annulus pressures were picked up by sensors, and the difference between the two pressures was then calculated.
3. Then, the height of the liquid column from the pressure difference was estimated, neglecting gas density.
4. Next the height of the gas column was estimated using well depth and liquid column height.
5. Then the average pressure of the gas column was calculated using surface pressure and pressure at gas-liquid interface.
6. The super-compressibility factor for gas at average pressure and temperature in gas column was then estimated.
7. The pressure at the gas-liquid interface was then calculated using surface pressure, the super-compressibility factor, and the assumed gas column height.
8. Next the liquid column height was re-estimated using the bottom-hole pressure and the estimated gas-liquid interface pressure.
9. Steps 4 through 8 were then repeated until the calculated pressure at the gas-liquid interface converged.

10. Finally, the average gas column pressure and the gas column height were used to calculate the gas volume at standard conditions.

To ensure that the conditions of continuous gas and liquid columns were valid at the end of an experimental run, the following procedure was developed:

1. The well was shut in at the final pressures.
2. Pressures were observed at the annulus, choke manifold, and bottom-hole for stabilization.
3. The pressures were measured and the gas volume was calculated.
4. The pressure was slowly bled off of the tubing, allowing the bottom-hole pressure to drop to the initial pressure (i.e., when the gas was placed in the well). Researchers then watched for signs of gas exiting the annulus via the entry into the tubing string.
5. The pressures were again measured and the gas volumes calculated.

The gas volumes calculated at the lowest pressure proved to be the most accurate because the physical volume of the gas storage space was maximized and the liquid volume was minimized. The calculation procedure was strongly affected by errors in calculated liquid height when gas volumes were low (i.e., at higher pressures).

The accuracy provided by the data collection system was acceptable; however, short periods (less than 5 minutes) of random data spikes occurred in some signals. The source of these variations could not be isolated and were assumed to come from the electrical system. To address these variations, all of the data were plotted and analyzed graphically. This resulted in a consistent method for evaluating all pressures.

The timings for the data collection system and the controllers were also tested during the experimental design phase. The resulting system used three independent timers: data collection, one-second cycle; formation fracture controller, three-second cycle; and, pump rate controller, three-second cycle. While this system performed adequately for the water and low-viscosity mud tests, some situations, primarily mud with gas displaced under high pressure, occurred in which there seemed to be a noticeable time lag in fracture response. It was concluded that faster and more consistent control actions could be achieved by re-designing the timing system. Prior to the high-viscosity mud experiments, the timing was redesigned to utilize a single timer, operating on a one-second cycle, for all data collection and control.

A minor leak in the choke sealing assembly was discovered before the initial choke opening (i.e., before the choke pressure reached the opening condition). Since this condition did not occur once flow through the choke began, it was addressed by isolating the choke with a manual valve until the opening pressure (a flow condition) was reached. This technique was included in the experimental procedure.

Live-well Experimental Procedure

The steps in the experimental procedure were as follows:

1. The fluid in the well was circulated (down annulus and up tubing) to ensure that the fluid properties were consistent and no gas was entrained in the fluid.

2. The computer data collection system was started. Pressures were observed to ensure that the data collection system was working properly.
3. Gas at pipeline pressure (approximately 600 psi) was allowed to flow into the annulus, displacing fluid to the mud system.
4. Once gas flow stopped, the gas inlet valve was closed. The well system was allowed to stabilize.
5. Initial gas-in-place volume was calculated.
6. The formation fracture simulator was started at the desired setting for formation fracture and the valve isolating the choke was closed.
7. The pump was then started manually in neutral gear.
8. Computer control of pump was started. The operator first set the computer control to the same control current as the manual control. Next, the pump was put into gear, and the computer control was switched to a low pump rate. As the pump started, the control pump rate was increased gradually to the target pump rate.
9. All pressures and rates were observed. When the bottom-hole pressure approached the fracture pressure, the valve isolating the choke was opened.
10. Observations of pressure behavior and gas flare at the flare stack were used to determine when gas removal from the well had ceased and the system had reached equilibrium. At this time, the pump was stopped. The well was automatically sealed at this point. The drop in bottom-hole pressure due to cessation of pumping caused the fracture simulator to close.
11. Pressures were observed to determine when all gas in the annulus had migrated up and separated from the liquid.
12. Pressures were recorded.
13. The tubing was allowed to flow through a separate manual control choke. The bottom-hole pressure was gradually reduced to allow the gas to expand in the annulus without allowing any gas in the annulus to flow into the tubing. The bottom-hole pressure was not allowed to drop below the original pressure when gas was placed in the annulus.
14. Pressures were observed and allowed to stabilize.
15. The volume of gas remaining in the well was calculated from the pressures.
16. The removal efficiency was calculated from the initial and final gas volumes in the well.

Inclined Flow Loop Experiments

The experimental program conducted in the inclined flow loop consisted of:

1. Construction of the experimental system;
2. Preliminary tests for adjustment of the apparatus;
3. Tests with air/water mixtures at different inclinations;

4. Tests with two air/polymer mixtures at different inclinations.

Inclined Flow Loop Apparatus

The flow loop is about 45 ft long (see Figure 3.4) and can be inclined at any angle between horizontal and vertical. During experiments liquid was injected at the "uphill" end of the test section. Air was injected approximately at the center of the apparatus. When all the gas was flowing in one direction, pressure actuated valves (QCVs, or Quick Closing Valves, in Figure 3.4) acted simultaneously to shut the system in allowing a direct measurement of holdup. The QCV closest to the pump is a three-way valve, which allows the liquid to bypass the test section and return directly to the tank.

The outer pipe of the annulus has an ID of 6.065 in, while the inner pipe used to simulate the drill string has an OD of 2.375 in. The drill string is locked in a fully eccentric position along the bottom of the outer pipe as this was felt to better simulate the drill string in a deviated well. A pressure gauge was installed at both ends of the test section to measure annulus pressure.

Fluids were handled by two separate systems. Liquid was stored in a 20-barrel tank and circulated through the apparatus with a centrifugal pump. A turbine-type flow meter was used to measure the liquid rate into the system, while a known volume of liquid flow out of the system was timed to determine liquid rate out. Volume of the test section was 70 gallons. Air was supplied through a regulator from a large tank charged by compressors. A rotameter with a pressure gauge was used to measure the flow rate of gas into the test section.

A separator vented counter-current gas and allowed gas flow rate to be measured (Figure 3.4) with a pressure gauge and two rotameters (two were needed as flow rates varied widely). Since air flow in and counter-current air flow out were known, co-current air flow was taken as the difference between the two. Of primary interest was the liquid velocity needed to move the gas downward, so that it could be successfully pushed down the well annulus and into a fracture. Actual gas velocities of the larger bubbles were also determined by means of a video camera.

The liquid phases adopted for the tests were fresh water and two water-based polymer muds. The first mud has a density of 8.4 ppg, a plastic viscosity of 3.9 cp, and a yield point of 9.5 lb/100 ft^2. The second mud was 8.4 ppg, and had a plastic viscosity 4.3 cp, and a yield point of 16.1 lb/100 ft^2.

The chosen parameters for the test matrix were the superficial gas velocity (U_{sg}) and the superficial liquid velocity (U_{sl}). The apparatus was capable of handling a range of superficial liquid velocities up to about 2.3 ft/sec and a range of superficial gas velocities up to about 1.0 ft/sec.

Inclined Flow Loop Test Procedure

An experimental run begins with the loop locked at the desired angle and all the valves open. The gas rate is then adjusted to the desired rate, followed by the liquid rate. When a steady state is reached, the video camera is started, and measurements are taken. Pressures at both ends of the test section are recorded along with air injection temperature, annulus temperature, separator pressure, and counter-current gas rate out. If the flow of air was only in one direction, the air actuated valves were closed and a direct holdup measurement made. Liquid rate was then adjusted for the next run. Frictional pressure loss increased annulus pressure linearly as the liquid rate increased, so corrections were made to determine actual gas rate in the annulus. During the polymer runs, fluid properties were measured with a viscometer and mud balance at least every two hours.

After all runs were made, the video-tape was analyzed to determine holdup on the co-current side, and actual bubble velocity on the counter-current side. Marks were made every foot on the pipe on the counter-current side, and bubbles were timed as they passed these marks. An average of several bubble velocities was taken as a representative gas velocity (U_g). Since U_{sg} was also known, void fraction could be determined. For the large vertical deviation angles studied, counter-current flow was always in the slug regime. Co-current flow was always stratified, which allowed a holdup measurement from the video-tape. It was assumed that visual distortion from refraction could be neglected for stratified flow. The height of the water on the tape was measured with a ruler, and an area formula was used along with ratio of the apparent diameter of the pipe to actual diameter to calculate the void fraction. Actual gas velocity could then be calculated from material balance considerations and knowledge of void fraction.

The results of the flow experiments conducted in both the inclined flow loop and the research well were combined and analyzed together. These results are described in the next chapter.

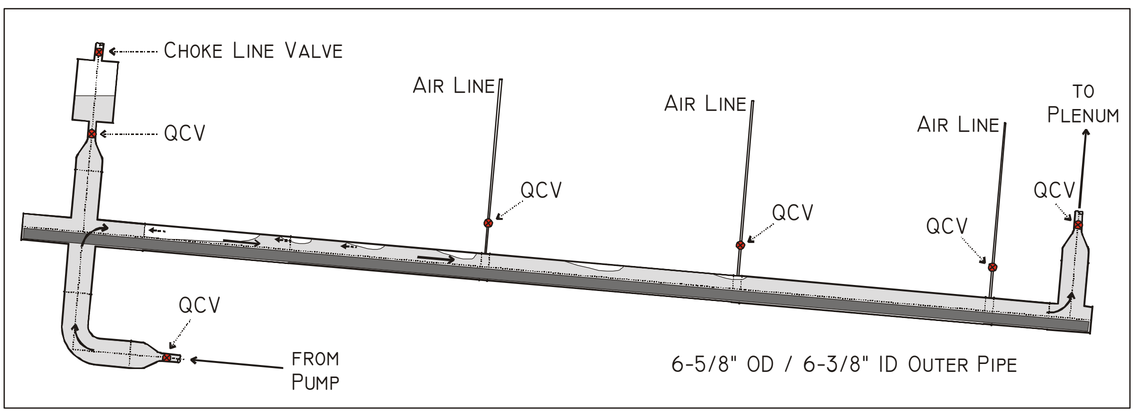

Figure 3.4 – Experimental Inclined Flow Annular Flow Loop

Chapter 4

Experimental Results

Experiments were conducted using both water and a low viscosity drilling fluid. Results obtained using water are felt to be representative of many well control situations during work-over or well completion operations. Results obtained using drilling mud or polymers can be applied to well control situations during drilling operations.

Twelve experimental runs were completed using the live-well system and two were completed using the inclined flow loop. Nine runs were made using water, five using a low-viscosity mud, and one using a low viscosity polymer as the bullhead fluid. **Table 4.1** shows the properties of the three fluids used.

Table 4.1 Properties of Bullhead Fluids

Fluid	Density, ppg	Plastic viscosity, cp	Yield Point, lb/100sf
Water	8.34	1	0
Mud	8.81	12	7
Polymer	8.4	4	10-16

Prior to the start of each bullhead simulation conducted in the research well, gas was allowed to flow into the annulus directly from the pipeline. This flow continued until equilibrium was reached with pipeline pressure and the height of the gas column in the well. The balance between the pipeline pressure and the fluid density resulted in gas column heights of approximately three-fourths of the well depth. Due to variations in gas pipeline pressure with time, there were small differences in initial gas column height and corresponding differences in initial gas volume. To investigate the effect of initial gas column height and volume, one experiment was repeated with an initial gas pressure of one-half of pipeline pressure.

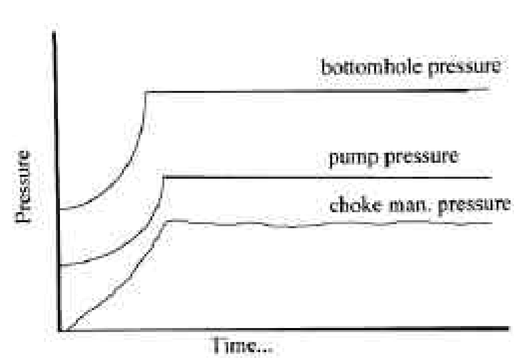

Figure 4.1: Typical pressure profiles during experiments.

Figure 4.1 shows the typical pressure traverse during an experimental run. The bottom-hole pressure, pump pressure and choke manifold pressure gradually increase until the fracture opens. Thereafter, the bottom-hole pressure opposite the simulated fracture remains constant, within the capability of the controller. The pump pressure trend is essentially horizontal when there is minimal gas removal. When significant amounts of gas are removed, the pump pressure either has a constant downward slope or step drop(s) and a downward slope. The choke manifold pressure is either horizontal or of downward slope, with some fluctuations. The gas removal tends to be more continuous at lower rates and when water is used, while the gas tends to exit more in slugs at higher injection rates and especially when mud is used. Experiments were always continued until gas was no longer being recovered.

Table 4.2 provides a summary of the initial and final gas pressures for each run, with the calculated gas column heights and volumes (at standard conditions) and the removal efficiencies. The average (superficial) annular injection velocities for the bullhead fluids are also shown in Table 4.2.

The removal efficiency for the experimental run with water, a fracture pressure of 2,000 psi, and a 12.50 gpm injection rate (marked by "*" in Table 4.2) was inferred from observations made during and after the run. After the experiment, the well was allowed to stabilize for 6 hours. However, during further inspection, it was apparent that gas had leaked through a manifold valve and entered other piping and wells. This caused significant losses of gas from the estimated gas volume not removed from the well, and thus an erroneous removal efficiency that was too high. During the experiment, which was conducted at night, no gas was seen at the flare. In addition, water was found in the flare line, further confirming that no gas had left the well via the fracture flow path. Gas was observed at the flare in all other experiments, which had calculated removal efficiencies varying from 18.8 to 98.5%. Also, during the experiment, there was no decline in pump pressure or choke manifold pressure; in all other experiments changes were observed in one or both of these pressures, with choke manifold pressure changes typically being related to gas activity at flare. Based on these considerations, it was estimated that no gas was removed in this run by bullheading and that the gas removal efficiency was 0%.

Table 4.2 - Gas Volume Measurements and Injection Velocities.

Fluid	Fracture Pressure, psi	Pump Rate, gpm	Avg. Annular Velocity, fps	Initial Gas Pres, psi	Initial Gas Height, ft	Init.ial Gas Vol, SCF	Final Gas Pres, psi	Final BHP, psi	Final Gas Vol, SCF	Rem. Eff., %
Water	2,000	12.50	0.174	650	1,572	12,094	*	*	*	0.0*
Water	2,000	25.00	0.347	589	1,404	10,001	498	680	8,123	18.8
Water	2,000	37.50	0.521	644	1,466	11,502	381	716	4,552	60.4
Water	2,000	50.00	0.695	644	1,613	12,659	109	734	422	96.7
Water	2,000	37.50	0.521	320	740	2,710	172	743	923	65.9
Water	3,000	37.50	0.521	627	1,445	10,944	483	770	6,292	42.5
Water	3,000	50.00	0.695	690	1,616	13,716	1158	1930	300	97.8
Mud	2,000	12.50	0.174	607	1,324	9,692	517	779	7,544	22.2
Mud	2,000	18.75	0.260	596	1248	8,953	380	777	4,098	54.2
Mud	2,000	25.00	0.347	616	1337	10,007	109	770	419	95.8
Mud	3,000	12.50	0.174	625	1,344	10,126	462	725	6,624	34.6
Mud	3,000	25.00	0.347	603	1315	9,568	116	867	146	98.5

The most important columns in Table 4.2 are the average annular velocity pumped and the resulting gas removal efficiency achieved. A zero removal-efficiency implies that the upward slip velocity of the smallest bubbles formed was in excess of the downward annular velocity used. A removal efficiency of 100 % implies that the downward annular velocity was greater than the upward slip velocity of the largest bubbles formed. If only a small range of bubble sizes are formed, then the transition from zero to 100% gas removal efficiency should occur over a narrow range of annular velocities. In order for bullheading operations to be completely successful, a gas removal efficiency near 100% would be needed.

Figure 4.1 shows the removal efficiencies for the experiments plotted as a function of injection rate, with the runs grouped by fluid type and fracture pressure. A shorthand nomenclature was used to identify the experimental runs for use on plots. Each run was identified by bullhead fluid, fracture pressure, and, optionally, gas column height. For example, the first experiment was identified as "water, 2000 frac." The following observations were made based on Figure 4.1:

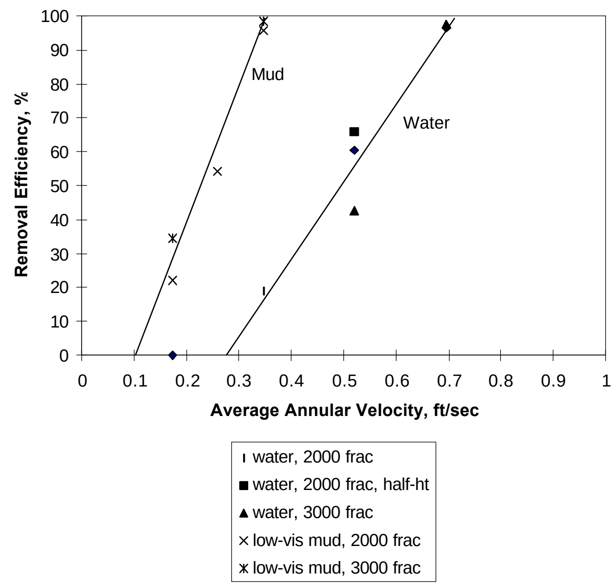

Figure 4.1: Removal efficiencies for Experiments.

1. Removal efficiency increases with increasing injection rate (downward fluid velocity) for a given fluid and fracture pressure.
2. At a given injection rate, the removal efficiency for mud is much higher than for water.
3. A zero gas-removal efficiency was observed to occur at average annular pumping velocities of up to about 0.1 ft/sec for mud and about 0.3 ft/sec for water.
4. A gas removal efficiency of 100% was observed to occur for average annular pumping velocities above about 0.35 ft/s for mud and about 0.7 ft/sec for water.

For concurrent gas-liquid flow in long vertical or inclined annuli, it is often convenient and useful to plot the average gas velocity as a function of the average mixture velocity (Zuber-Findlay plot). For a gas kick in an annulus of constant cross sectional area, the average mixture velocity in the gas contaminated kick region can be taken as equal to the velocity of the uncontaminated liquid above the gas kick region. This relatively simple approach, which typically considers only the most important factors affecting gas velocity, has been found to allow significantly improved simulation of well control operation over that which can be achieved neglecting gas slip. In this study, the use of Zuber-Findlay plots was extended to counter-current gas migration by considering a downward pumping velocity to be negative and a conventional upward circulation velocity to be positive. Similarly, an upward gas velocity is considered positive while a downward gas velocity is considered to be negative.

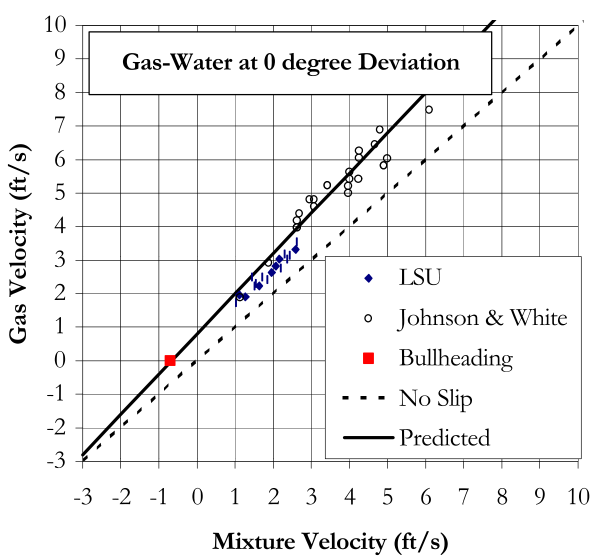

Figure 4.2 – Gas Velocity for Water in a Vertical Annulus

Shown in Figure 4.2 is a Zuber-Findlay plot that combines data taken in the LSU inclined flow model (6-in ID) and data taken in the research well (6-in. ID). In addition, published data [Johnson and White (1991)] taken at the Schlumberger Cambridge Research facility in a larger (8-in. ID) model of a concentric annulus is also plotted (points shown as open circles). The lower data point shown (solid square) corresponds to the minimum downward pumping velocities for 100% gas removal efficiencies in the research well experiments. The solid line represents the results that would be predicted by the computer model developed in this work.

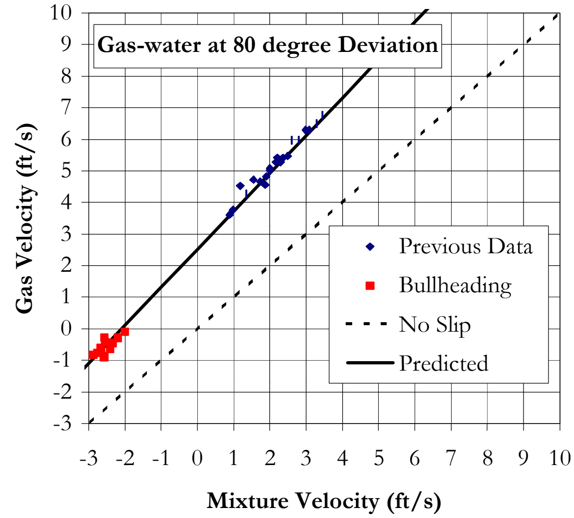

Figure 4.3- Gas Velocity for Water in Inclined Annulus at 80-degree vertical deviation

The computer model determines the gas velocity based on the intercept and slope of straight-line segment of the Zuber-Findlay plots. As many as five straight-line segments are used in the model to cover the entire range of mixture velocities and resulting flow patterns. The segments used include:

1. no-slip (or negligible-slip) downward flow (bullhead) region
2. laminar flow region (used only for drilling muds)
3. turbulent flow region
4. transition to no-slip upward flow
5. no-slip (or negligible-slip) upward flow region

The results predicted by the computer model for a low-viscosity Newtonian fluid are shown in Figure 4.2. This entire range could be modeled with only one straight-line segment (Segment 3) for the range of mixture velocities that are important for bullhead well control operations. The correlation for estimating the effect of vertical deviation angle on gas velocity was based on data obtained in the inclined flow loop.

The gas slip velocity, V_{slip}, in low-viscosity Newtonian fluids of density, ρ_{liq} , at zero mixture velocity (intercept) and at various vertical deviation angles, Θ, is defined by the following equation:

$$V_{slip3} = (0.804 + 0.063q - 0.00286 * \Theta^2 +$$

$$0.0000787\Theta^3 - 6.30E-07\Theta^4)\sqrt{\frac{r_{liq} - r_{gas}}{r_{liq}}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4.1)$$

The slope of the gas velocity versus mixture velocity correlation was found to be approximately constant at a value of about 1.2 for low-viscosity Newtonian fluids over the range of mixture velocities important for bullheading operations.

Shown in Figure 4.3 is a comparison of the predicted and measured gas velocities obtained in the inclined flow model at a vertical deviation angle of 80 degrees. The set of data points having a negative velocity were for co-current flow achieved under bullhead conditions in the inclined flow loop (Solid Squares). These data correspond to conditions of sufficient gas concentration (greater than 25%) to represent efficient bullhead conditions. The gas slip velocity was found to increase with deviation angle and reach a maximum at about 60 degrees. Slip velocities remained higher for an inclined annulus than for a vertical annulus to very high values of deviation angle, before going to zero for horizontal flow (90 degrees vertical deviation).

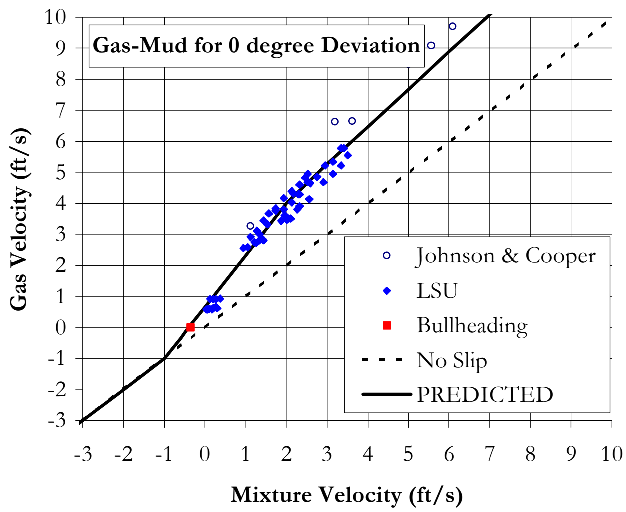

Figure 4.4- Gas Velocity for Mud in Vertical Annulus

Shown in Figure 4.4 is the Zuber-Findlay plot obtained for a non-Newtonian drilling fluid in a vertical annulus. The counter-current gas slip velocity in a non-Newtonian drilling fluid during bullhead operations was found to be much less than for water. In addition, at low Reynolds numbers and vertical deviation angles, the slope of the Zuber-Findlay plot was observed to change significantly. This is thought to be due to increasing apparent viscosity at decreasing annular shear rates. For turbulent flow conditions, the gas-mud correlation obtained for the slip velocity (apparent intercept) at various vertical deviation angles is defined by the following equation:

$$V_{slip3} = (1.663 + 0.0279\theta - 0.00876*\Theta^2 + 0.000023\Theta^3$$
$$- 2.06E - 07\Theta^4)\sqrt{\frac{\rho_{liq} - \rho_{gas}}{\rho_{liq}}} \text{..(4.2)}$$

For laminar flow conditions, the correlation obtained for the slip velocity (intercept) at various vertical deviation angles is given by:

$$V_{slip2} = (0.19 + 0.00966q - 0.000477 * \Theta^2 + 0.000015\Theta^3$$

$$-1.23E - 07\Theta^4)\sqrt{\frac{r_{liq} - r_{gas}}{r_{liq}}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(4.3)$$

The slope of the straight-line segment corresponding to turbulent flow on the Zuber-Findlay plot is predicted using:

$$m_3 = 1.25 + 0.004 * \Theta \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(4.4)$$

The slope, m_2, of the straight-line segment corresponding to laminar flow is chosen to connect the intercept, V_{slip2}, to the point on the second straight-line segment corresponding to the transition to turbulent flow at a Reynolds Number of 2600. The transition to no-slip flow is assumed to occur at the point on the turbulent flow straight line segment where the gas velocity is predicted to be equal to the mixture velocity.

As the vertical deviation angle increases to a high value, the straight line Zuber-Findlay plot representation of the inclined flow loop data taken with a non-Newtonian mud or polymer becomes more approximate. This can be seen in Figure 4.5. The gas velocities observed for negative liquid velocities (bullheading conditions) were higher than expected based on slip velocities measured previously in the inclined flow loop at very slow, but positive liquid velocities. The model shown was felt to be adequate for design calculations.

A computer program was developed to allow the results of the experimental program described in this chapter to be applied in the field. The computer program is described in the next chapter.

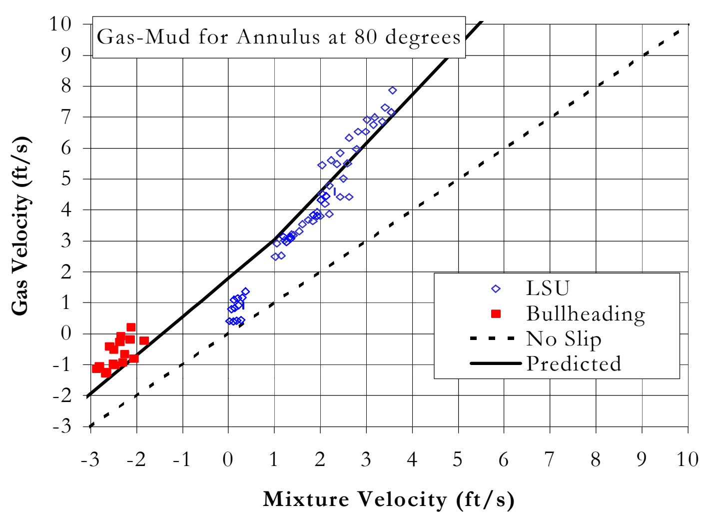

Figure 4.5 – Gas Velocity in Mud for Inclined Annulus at 80-degree vertical deviation

Chapter

5

Computer Model for Analysis of Bullhead Kill Operations

The countercurrent gas slip velocity correlation developed in this study and described in the previous chapter were incorporated into new public domain software for the analysis of Bullhead Kill Operations. The new software is being made available for use by MMS, by well control trainers, by drilling contractors, and by oil and gas operators.

A new computer model was developed to permit a Bullhead Kill Operation to be evaluated for a given underground blowout situation encountered during drilling operations. The new software was developed using the countercurrent gas slip velocity correlation described in the previous chapter of this report. Prior to this work, the authors know of no public domain software that was available for predicting the performance of a Bullhead Kill Operation for multiphase conditions involving natural gas. Public access to this type of analysis was previously available only through use of some of the more advanced and costly well control training simulators and the ability of these proprietary simulators to accurately model countercurrent gas slip is largely unknown.

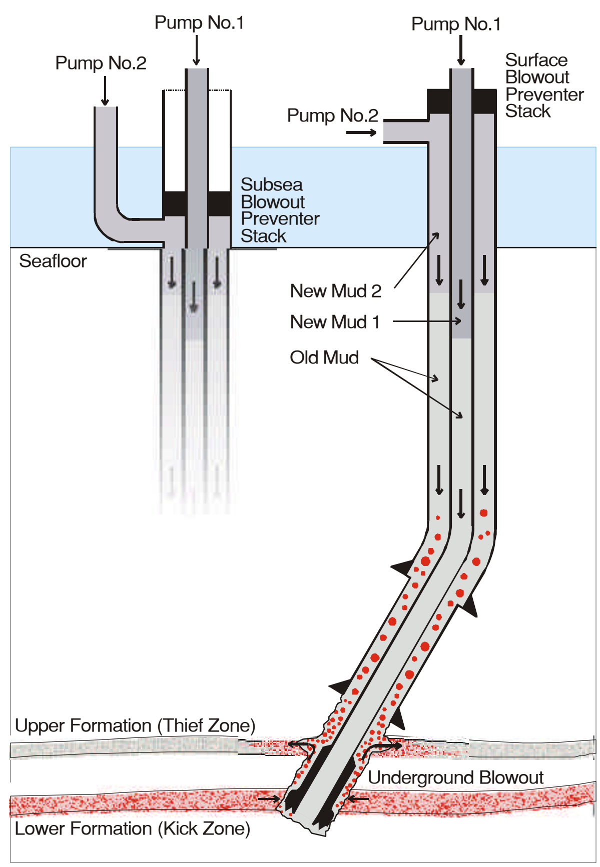

Figure 5.1: Bullhead Kill Process

Applications

The Bullhead Kill process that can be modeled using the new software is illustrated in Figure 5.1. The applicable situation is an underground blowout in which formation gas and water enters the well from a gas bearing formation located at the bottom of the well. Formation fluid and drilling fluid exits the well through a hydraulic fracture and into an upper formation at some specified depth above the hole bottom. The well can be either a vertical or a directional well and can have non-uniform drill string and annular diameters. Kill fluids having different densities and viscous properties can be pumped down the drill string and annulus. The flow geometry present for either a surface or a sub sea Blowout Preventer Stack can be accommodated. The focus of this research was on underground blowouts from a gas bearing formation and the program is not designed for analysis of a Bullhead Kill Operation on a well not experiencing an underground blowout. For example, it is not suitable for analysis of a Bullhead Kill Operation conducted as part of a well work-over operation with only one set of open perforations. The program is also not intended for analysis of an underground blowout from a non gas-bearing formation since well control operations for liquid flow are much easier to control and are relatively simple to analyze with a single phase wellbore hydraulics model.

Required User Agreement

The right to use the new program is granted with the understanding that the USER assumes ALL RESPONSIBILITY for use of the program and of the program results. Well Control Simulation is an inexact science and NO WARRANTY is made or implied by the program authors, by Louisiana State University, or by the Minerals Management Service as to the suitability of the software for the users computer system or the accuracy of the calculation results. Every effort should be made to independently verify results using field observations whenever possible. Before using this program, the user must understand and agree to these conditions. This agreement is verified automatically at the start of each program run.

Computer Requirements and Program Execution Procedure

The new software was developed on a personal computer having a Pentium II Central Processing Unit (CPU), 384 Megabytes of Random Access Memory (RAM), and using a Windows 98 Operating System. It has been tested on a number of computers having later generation (newer) Pentium Processors and 256 Megabytes of RAM or more. A minimum memory requirement has not been determined and may depend on the operating system in which the program is used. It is a DOS based program and should run on any machine that supports the DOS environment and has a math co-processor included in the CPU.

It is highly recommended that a File Folder (Sub-directory) be created for each set of conditions (input data) that will be investigated and saved. Copy both the program execution module "BULLHEAD.EXE" and an input data file "INPUT.DAT" into this sub-directory. It is often convenient to start with an example input data file from another case and modify the fields containing the input data to fit the new case to be investigated. The program can then be executed by opening the File Folder Window (Sub-directory) containing these two files and double clicking on BULLHEAD.EXE. The program opens a DOS window that must be closed when the program finishes by clicking in the window and hitting a return when requested to do so. Upon Execution, output files are created and placed in the File Folder (Sub-directory). These output files can be opened with any text editor. In a Microsoft Windows operating environment, Notepad, Wordpad, or Word can be used to view the output files. The output files are in table form that can be easily imported or pasted into spreadsheet software such as Microsoft Excel, or graphing software.

Theoretical Basis

The solution technique used in the program is summarized in the flow chart shown in Figure 5.2. After reading the input data set that defines the conditions for the Bullhead Kill Operation of interest, the program first computes the value of a number of coefficients that will remain constant throughout the entire analysis. The drill string and annular flow path is then broken into a number of discrete cells of constant diameters, to permit a finite distance numerical analysis procedure to be applied. The geometry and cell volumes of the drill string and annular flow paths are written in two output text files, GEOM_P01.Txt and GEOM_A01.Txt. This permits the program user to verify that the flow path geometry was correctly described in the input data file.

The cell contents are initialized as mud, gas, or water, as defined in the input data. A time step size is then selected based on the minimum cell volume and the maximum pump rate that will be used. The main program loop is then started, which consists of:

- Setting the surface pump rates and kill fluids being injected down the annulus and drill string for the time step;

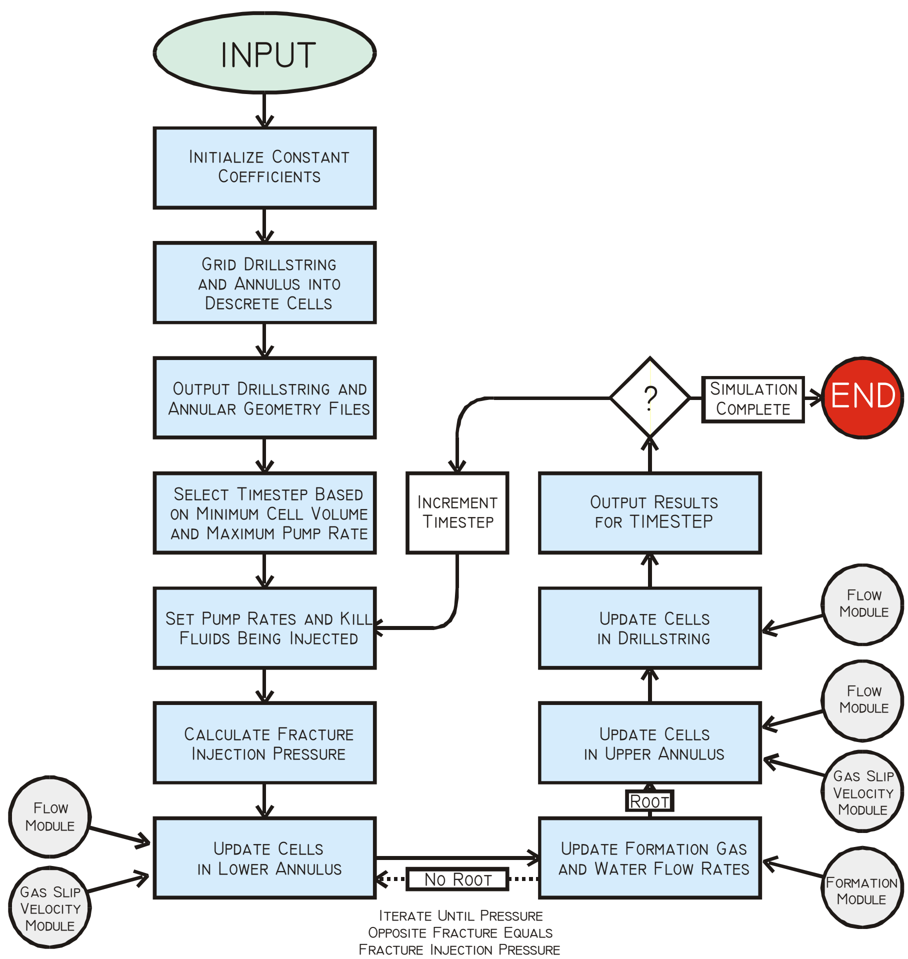

Figure 5.2 – Program Flow Chart

- Calculating the Fracture Injection Pressure at the exit point (upper formation);
- Updating the cell fluid contents, fluid properties, temperature, and pressure for the cells in the lower annulus between the lower formation (kick zone) and the fluid exit point (This involves an iterative process to determine the gas and water feed rate at the bottom of the interval that produces the known fracture injection pressure at the top of the interval);
- Updating the cell fluid contents, fluid properties, temperature, and pressure for the cells in the upper annulus between the surface and the exit point (upper formation);
- Updating the cell fluid contents, fluid properties, temperature, and pressure for the cells in the drill string flow path;
- Writing output for the time step to the primary output text file, KILL_SUMMARY.TXT and to various snapshot files when specified in the input data for the time interval of interest (The Kill Summary file provides information at a few key points versus time and the Snapshot files provide supplemental information at a given time versus depth); and
- Incrementing time to the next time step and then repeating the main program loop until the last time specified is reached.

Primary program modules needed to perform this analysis include the formation module, the pipe and annular fluid flow module, and the gas slip velocity module. The gas slip velocity module used was described in the previous chapter.

Formation Flow Module

The Reservoir Module calculates the volumetric flow rate at the sand face for a given reservoir system at a given time. The module was initially constructed to be able to handle unsteady state conditions and either a closed boundary or a constant pressure boundary. However, this level of complexity was found to be unnecessary for underground blowout analysis. In order to keep the software simple and easy to use (with minimal input data required), the final version of the module was limited to the case of a constant pressure at the outer boundary and steady state conditions. This simplifying assumption was found to make only minor differences in analysis results for underground blowouts of short duration (a few days or less) from formations having a high productivity.

The total pressure drop in the reservoir, which is equal to the current pressure difference existing between the flowing well and the reservoir, may be attributed to three phenomena. The first and most significant portion of the total pressure drop is due to Darcy (non-turbulent) flow within the reservoir outside of the near-well region. In the near-well region, additional pressure drops may be present due to (1) alteration of the permeability of the formation (skin) or (2) partial penetration of the well or (3) the relative geometry of the well and the drainage volume or (4) turbulent (non-Darcy) flow. The total pressure drop between the well, p_{wf}, and reservoir, p_r, due to flow may be expressed mathematically in the following manner:

$$
\begin{aligned}
p_R - p_{wf} &= \Delta p_{total} \\
&= \Delta p_{Darcy} + \Delta p_{skin} + \Delta p_{partial} + \Delta p_{geom} + \Delta p_{non-Darcy}
\end{aligned} \tag{5.1}
$$

By superposition, the total pressure drop at any time for a multi-rate well is equal to the sum of the individual pressure drops associated with each change in well rate. Since both the pressure drop due to skin and the pressure drop due to non-Darcy flow are near-well phenomena, each of these pressure drops are associated with the *current* change in well rate *only*. Thus, for a multi-rate well, Equation (5.1) may be re-written as follows:

$$
\begin{aligned}
(p_R)_0 - (p_{wf})_n &= \sum_{i=1}^{n} \Delta p_i \\
&= \sum_{i=1}^{n}\left(\Delta p_{Darcy}\right)_i + \left(\Delta p_{skin} + \Delta p_{partial} + \Delta p_{geom} + \Delta p_{non-Darcy}\right)_n
\end{aligned} \tag{5.2}
$$

where n designates the number of changes in rate experienced by the well since the start of production and the subscript, 0, designates an initial condition prior to the start of production.

Darcy Flow Component

The pressure drop due to Darcy flow associated with a change in well flow rate, q, is dependent upon (1) the properties of the reservoir and the flowing fluid, (2) the relative size, areal position, and orientation of the well within the reservoir, and (3) the volumetric flow rate of the well. The effect of the reservoir and fluid properties such as permeability, thickness, and viscosity are reflected in the Darcy Flow Coefficient (C_R) which is may be considered constant for a given reservoir/fluid system. The effect of the relative size, areal position, and orientation of the well within the reservoir is reflected in a dimensionless pressure function (p_D). The pressure drop due to Darcy flow associated with the i^{th} change in well rate may be expressed as follows:

$$
(\Delta p_{Darcy})_i = C_R\{q_i - q_{i-1}\}(p_D)_i \tag{5.3}
$$

where the dimensionless pressure function depends upon either the elapsed time (unsteady-state) or the geometry of the reservoir/well system (steady-state) or both (pseudo-steady-state) and the orientation of the well within the reservoir (vertical or horizontal).

Skin Component

The additional pressure drop due to alteration of the reservoir permeability near the well which is referred to as *skin* is accounted for with a skin factor, S. The pressure drop due to the skin is equal to the Darcy Flow Coefficient (C_R) multiplied by the volumetric flow rate of the well multiplied by the skin factor (S_F). If the permeability near the well is unchanged, the skin factor (S_F) is equal to zero. If the permeability near the well is less than the surrounding reservoir, the skin factor (S_F) is greater than zero (positive). If the permeability near the well is greater than the permeability in the surrounding reservoir, the skin factor is less than zero (negative).

$$
\Delta p_{skin} = C_R\{q_n - q_{n-1}\}S_F \tag{5.4}
$$

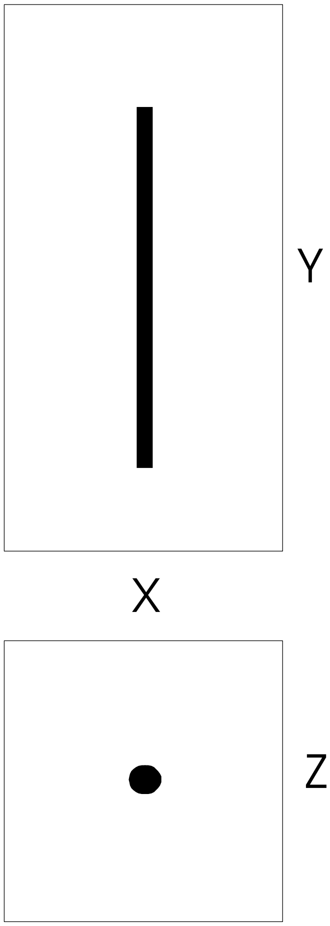

Figure 5.3 – Reservoir Shape

Partial Penetration Component

Likewise, the additional pressure drop associated with partial penetration of the well within the reservoir may be treated as a skin effect and calculated as follows:

$$\Delta p_{partial} = C_R \{q_n - q_{n-1}\} S_R \tag{5.5}$$

where S_R is calculated based on the position of the well within the reservoir drainage volume using an expression presented by Babu and Odeh (1989) for partial penetration of a horizontal well. The expression may be applied by analogy to predict the "skin factor" associated with the partial penetration of a vertical well.

Geometry Component

Likewise, the additional pressure drop due to the relative geometry of the well and the drainage volume may also be treated as a skin effect and calculated as follows:

$$\Delta p_{geom} = C_R \{q_n - q_{n-1}\} \ln(C_H) \tag{5.6}$$

where $\{\ln(C_H)\}$ is calculated using an expression presented by Babu and Odeh (1989). Represented in Figure 5.3 is an illustration of a horizontal well positioned in the center of a rectangular drainage volume. The upper figure represents the areal view and the lower figure represents a cross-sectional view.

The geometry term is a function of (1) the aspect ratio ($^X/_Z$) of the reservoir in the plane perpendicular to the length of the well, (2) the vertical to horizontal permeability ratio, and (3) the position of the well within the reservoir drainage volume. No correction for the geometry of the reservoir/well system is required if (as shown left):

- the plane of the reservoir perpendicular to the length of the well is a square;
- the vertical permeability is equal to the horizontal permeability; and
- the well is located in the center of that square.

This condition is analogous to a vertical well located in the center of a circular, isotropic reservoir.

Turbulent Flow Component

The additional pressure drop near the well due to turbulent flow is accounted for with a Non-Darcy Flow Coefficient (D_R). For the flow of liquids, the Non-Darcy term is generally negligible, but for gases which often flow at much higher rates, the Non-Darcy term can be significant. The Non-Darcy pressure drop may be expressed as follows:

$$\begin{aligned}\Delta p_{Non-Darcy} &= C_R\{q_n - q_{n-1}\}[D_R\{q_n - q_{n-1}\}] \\ &= C_R D_R\{q_n - q_{n-1}\}^2\end{aligned} \tag{5.7}$$

By combining Equations (5.2) through (5.5) the following expression which relates the total pressure drop at any time (t_n) to the rate history of the well through time (t_n):

$$\begin{aligned}(p_R)_0 - (p_{wf})_n = \sum_{i=1}^{n}[C_R\{q_i - q_{i-1}\}(p_D)_i] + \\ C_R\{q_n - q_{n-1}\}(S_F + S_R + \ln C_H) + C_R D_R\{q_n - q_{n-1}\}^2\end{aligned} \tag{5.8}$$

Notice that for a constant rate well, n would be equal to 1 and n-1 would be equal to 0. The rate, q_1, is a constant equal to q. The rate, q_0, is equal to the rate at t_0 which is equal to 0. Therefore, q_0 is always equal to zero. In this instance, Equation (5.6) reduces correctly to the constant (single) rate case as follows:

$$(p_R)_0 - p_{wf} = \sum_{i=1}^{1}\Delta p_i = C_R q\{p_D + S_F + S_R + D_R q\} \tag{5.9}$$

Since the flowing bottom-hole pressure is calculated for each time step elsewhere in the program, the flowing bottom hole pressure is always known to the Reservoir Module. The initial reservoir pressure, the Darcy Flow Coefficient, the skin, and the Non-Darcy Flow Coefficient are all constants which may be input directly or estimated in the Initialization Module based on input and selections made prior to running the program. As shown in Equation (5.7), the only unknown at the first time step is the rate which the well maintained from time zero to the end of the first time step. At each additional time step, each of the previous well rates are known from similar calculations at the previous time steps. In each instance, the only unknown in Equation (5.6) is the well rate for the current time step. In this manner, the rate of the well during each successive time step can be predicted and passed on to the rest of the program.

The Dimensionless Pressure Function

The dimensionless pressure function is a means of relating a given rate that has been sustained for a given time to the pressure drop associated with Darcy flow. The dimensionless form of the function allows it to be applied universally to reservoirs as long as the boundary conditions of the reservoir may be reasonably approximated by the boundary conditions inherent in the derivation of the dimensionless pressure function. Both exact and approximate solutions to the dimensionless pressure have been employed in the Reservoir Module. Each function originates from a solution to the Diffusivity Equation, which is the governing relationship between time and pressure in porous media. Depending upon the defining boundary conditions, specific forms of the dimensionless pressure function can be derived.

Steady-State Flow

The simplest dimensionless pressure function arises from the assumption of steady-state, radial flow. For this case, the dimensionless pressure function for a vertical well of radius r_w in a circular reservoir of radius r_e is exactly defined as follows (Craft and Hawkins, 1959):

$$p_D = \ln\left(\frac{r_e}{r_w}\right) \tag{5.10}$$

By analogy, the steady-state dimensionless pressure function for a horizontal well in a rectangular drainage volume may be expressed as follows:

$$p_D = \ln\left(\frac{\sqrt{A}}{r_w}\right) = \ln\left(\frac{\sqrt{(x_D h)}}{r_w}\right) \tag{5.11}$$

where A denotes the area of the reservoir in cross-section, x_D denotes the width of the drainage volume, and h denotes the thickness of the reservoir in the z direction as shown in Figure 5.3.

Pseudo-Gas Function for Gas Reservoirs

The pseudo-gas function is an integral that allows the behavior of flowing gases to be approximated with the solutions derived for a flowing liquid. All of the equations presented thus far are applicable to the flow of gases as well as liquids if the reservoir pressure and the flowing bottom hole pressure within the well in Equation (5.8 and 5.9) are replaced by their corresponding pseudo-gas function value. The pseudo-gas function is defined as follows:

$$m(p) = 2\int_0^p \frac{p}{\mu\ z}\,dp \tag{5.12}$$

where μ is the gas viscosity and z is the gas deviation factor. The equations used to calculate the various constants used in the reservoir module are given in Table 5.1 for English field units. In this table, permeability is in millidarcies, pressure is in psi, temperature is in degrees Rankine, and lengths are in feet.

Table 5.1 - Equations used for calculating reservoir constants used in the Reservoir Module.

Reservoir Constant	Equation	Equation Number
Darcy Flow Coefficient (C_R):		
For gas (psi-day/Mscf):	$C_R = \dfrac{50{,}302\, p_{sc} T_R}{k h T_{sc}}$ (absolute units)	(5.12)
Non-Darcy Flow Coefficient (D_R):		
For gas (day/Mscf):	$D_R = \dfrac{2.9124 x 10^{-14}\, \beta\, \rho_{sc}\, k}{\mu\, h}\left(\dfrac{1}{r_w} - \dfrac{1}{r_e}\right)$	(5.13)
Non-Darcy Beta Coefficient (β):		
For gas (1/ft):	$\beta = \dfrac{1 \text{ x } 10^7}{\sqrt{k}}$	(5.14)
Partial Penetration Factor (S_R):		

For Aspect Ratio <1.333 : $S_R = P_{xyz} + P'_{xy}$ where (5.15a)

$$P_{xyz} = \left(\frac{b}{L_w} - 1\right)\left(\ln\frac{h}{r_w} + \frac{1}{4}\ln\frac{k_x}{k_z} - \ln\left(\sin\frac{180z}{h}\right) - 1.84\right)$$

$$P'_{xy} = \frac{2b^2}{L_w h}\sqrt{\frac{k_z}{k_x}}\left\{f(x_1) + \frac{1}{2}[f(x_2) + f(x_3)]\right\}$$

$$f(x>1) = (2-x)[0.145 + \ln(2-x) - 0.137(2-x)^2]$$

$$f(x \le 1) = (-x)[0.145 + \ln(x) - 0.137x^2]$$

$$x_1 = \frac{L_w}{2b}\ ;\ x_2 = \frac{4\bar{y}_w + L_w}{2b}\ ;\ x_3 = \frac{4\bar{y}_w - L_w}{2b}$$

For Aspect Ratio > 1.333 : $S_R = P_{xyz} + P_y + P_{xy}$ where (5.15b)

$$P_{xyz} = \left(\frac{b}{L_w} - 1\right)\left(\ln\frac{h}{r_w} + \frac{1}{4}\ln\frac{k_x}{k_z} - \ln\left(\sin\frac{180z}{h}\right) - 1.84\right)$$

$$P_y = \frac{6.28Y_D^2}{X_D h}\frac{\sqrt{k_x k_z}}{k_y}\left[\left(\frac{1}{3} - \frac{\bar{y}_w}{Y_D} + \frac{\bar{y}_w^2}{Y_D^2}\right) + \frac{L_w}{24Y_D}\left(\frac{L_w}{Y_D} - 3\right)\right]$$

$$P_{xy} = \left(\frac{Y_D}{L_w} - 1\right)\left(\frac{6.28X_D}{h}\sqrt{\frac{k_z}{k_x}}\right)\left(\frac{1}{3} - \frac{x_w}{X_D} + \frac{x_w^2}{X_D^2}\right)$$

Geometry Factor (LnC_H):

$$\ln C_H = \left(6.28\frac{X_D}{h}\sqrt{\frac{k_z}{k_x}}\right)\left(\frac{1}{3} - \frac{x_w}{X_D} + \frac{x_w^2}{X_D^2}\right) - \ln\left(\sin\left[\frac{180z_w}{h}\right]\right) - \frac{1}{2}\ln\left[\frac{X_D}{h}\sqrt{\frac{k_z}{k_x}}\right] - 1.088 \tag{5.16}$$

Pipe and Annular Flow Module

Upstream of the exit, the pressure gradient, dp/dL, is determined from an expression for the conservation of momentum. According to the conservation of momentum, the total pressure gradient may be expressed as the sum of the pressure gradient due to hydrostatics, the pressure gradient due to friction, and the pressure gradient due to acceleration as follows:

$$\frac{dP}{dL} = \left.\frac{dP}{dL}\right|_h + \left.\frac{dP}{dL}\right|_f + \left.\frac{dP}{dL}\right|_a \tag{5.17}$$

Hydrostatic Component

The hydrostatic component of the flowing pressure gradient changes in a interval having a vertical deviation angle, *q*, and is computed using the following expression:

$$\left.\frac{dP}{dL}\right|_h = \bar{\rho}_e g \cos(\theta) \tag{5.18}$$

Frictional Component

The frictional component of the flowing pressure gradient is a function of the existing flow regime and flow path geometry. Depending upon these conditions, the frictional gradient may be expressed as follows:

Turbulent flow:

$$\left.\frac{dP}{dL}\right|_f = \frac{\bar{\rho}_{ns}\,\bar{v}_m^2}{2\,d_e} f\, e^s \tag{5.19a}$$

Laminar Pipe Flow:

$$\left.\frac{dP}{dL}\right|_f = \frac{\mu_{ns}\,\bar{v}_m}{1500\,d^2} e^s \tag{5.19b}$$

Laminar Annular Flow:

$$\left.\frac{dP}{dL}\right|_f = \frac{\mu_{ns}\,\bar{v}_m}{1000\,(d_2 - d_1)^2} e^s \tag{5.19c}$$

where v_m is the non-slip mixture velocity (total volumetric flow rate of all phases per unit area), μ_{ns} is the non-slip laminar-flow Newtonian viscosity of the mixture, d_e is the equivalent diameter of the section, and the Moody friction factor, f, as defined by the following expression:

$$\frac{1}{\sqrt{f}} = -2\,Log_{10}(0.27\frac{e}{d_e} + \frac{2.52}{N_{Rns}\sqrt{f}}) \tag{5.20}$$

where ε is the absolute roughness. Beck et. al. found that a value of 0.00065 in. for roughness gave good agreement with experimental data obtained in a model diverter having a diameter of 4.9 in. The non-slip Reynolds number, N_{Rns}, is defined as follows:

$$N_{Rns} = \frac{r_{ns}\,\bar{v}_m\,d_e}{m_{ns}} \tag{5.21}$$

where μ_{ns} is the effective turbulent-flow fluid viscosity of the mixture. The average viscosity of the mixture is estimated as the volume weighted average of the components of the mixture.

The term e^s in the expression for the frictional component of the pressure gradient represents the exponential function exp(s) and converts the single phase friction factor, f, to a multiphase friction factor using a correlation developed by Beggs and Brill and described in detail by Beggs (1991). This multiphase flow correlation was adapted for mud-gas mixtures in annuli over a wide range of inclination angles (0 to

90°) and a reasonable range of mud properties (8.5 - 12 ppg and 5-30 cp). The liquid volume fraction (hold-up) correlation used to determine the correlation parameters, s and y, were modified to be defined as follows:

$$s = 0 \qquad \text{for } \alpha_{gns} = 0 \tag{5.22a}$$

$$y = \ln \frac{1}{(1 - a_{gns})} \qquad \text{for } y > 1.0 \text{ and } \alpha_{gns} > 0 \tag{5.22b}$$

$$s = \ln(2.2\,y - 1.2) \qquad \text{for } 1.0 < y < 1.2 \tag{5.22c}$$

$$s = \frac{\ln y}{-0.0523 + 3.182\ln(y) - 0.8725[\ln y]^2 + 0.01853[\ln y]^4} \qquad \text{for } y > 1.2 \tag{5.22d}$$

For single-phase liquid flow, y is zero, s is zero, and e^s is one. As single-phase gas flow is approached, s approaches zero and e^s again approaches one. The gas slip velocity correlation used to calculate the gas volume fraction, α_g, was developed as part of this study and was described in the previous Chapter.

Acceleration Component

The third component of the pressure gradient is due to pressure changes caused by fluid acceleration. Acceleration effects were considered to be negligible for conditions of an underground blowout except for pressure drops at sudden restrictions in the drill string due to the presence of a measurement while drilling tool or a jet bit. For these components, the pressure drop was calculated using

$$\Delta p = \overline{r}_m \frac{\Delta \bar{v}_m^{\,2}}{2C_D^2} \tag{5.23}$$

where C_D is the discharge coefficient of the restriction, and usually has a value of about 0.95 for jet bit nozzles.

Program Verification

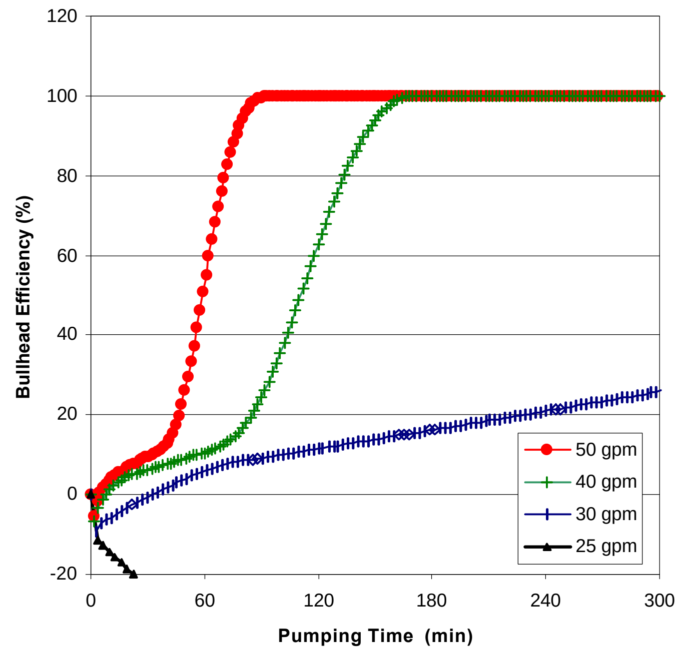

Figure 5.3 – Calculated Bullhead Efficiencies for LSU Research Well at a Fracture Pressure of 2000 psi with Low Viscosity Mud

The program was verified to the extent possible using experimental data collected in the LSU Research Well. The gas slip velocity correlation described in Chapter 4 provides a single maximum gas slip velocity whereas the true multiphase behavior results from a range of bubble sizes and gas slip velocities. Thus, it was expected that the program would yield lower values of Bullhead Efficiency than was measured for cases in which the predicted gas slip velocity was greater in magnitude than the average downward velocity of the kill fluid being pumped into the well at the surface. It was intended that the program would give a conservative estimate of the chance for success at marginal pump velocities.

Shown in Figure 5.3 are calculated Bullhead Efficiencies for the low viscosity mud used in the LSU Research Well at 25, 30, 40, and 50 gallon per minute and a simulated fracture pressure of 2000 psi. As expected and intended, the program results are conservative when compared to the experimental data. Recall from Table 4.2 and Figure 4.1 that Bullhead Efficiency was observed to increase from 22.2 to 95.8% as the pump rate was increased from 12.5 to 25 gallons per minute. Note that the program predicts a Bullhead Efficiency of 100% at 40 gallons per minute, and predicts a negative Bullhead Efficiency at 25 gallons per minute. The negative Bullhead efficiency occurs because the well was not initially completely gas filled in the experimental runs simulated and the program assumes an underground blowout below 1904 ft. The program indicates gas from below moves up countercurrent to the flow of mud and increases the gas volume above 1904 ft. The experimental program did not include gas injection on bottom since the intent was only to determine the pumping velocities that resulted in complete gas removal.

The program has also been verified using one field case history. This case will be discussed in the Final Report for Task 10, which will present four training modules based on case histories. It is recommended that the Program User seek to verify the program results with additional field data whenever data of sufficient quality are available. It has been difficult for the program authors to collect field data on Bullhead Kill Operations for Underground Blowouts because of the sensitive nature of this information.

Example Bullhead Kill Analysis

The use of the new software is most easily understood through use of an example. Consider a situation similar to the schematic shown in Figure 5.1 for a surface Blowout Preventer Stack.

Loss of circulation has previously been experienced at an equivalent circulating density of 18.6 pounds per gallon in the first sand below a 7.625-in. liner (internal diameter of 6.756 in.). The loss-circulation zone was at approximately 15,800 ft, which was about 200 ft below the 7.625-in liner. The liner extended from inside 9.625-in. casing (internal diameter of 8.525 in.) at 12,900 ft to a depth of 15,600 ft.

The well control event occurred after drilling the upper 50 ft of a known 50-millidarcy, 150 ft thick gas pay zone at a depth of 17,300 ft using a tapered drill string and a 6.5-in bit having a total flow area of 0.35 in^2. The drilling mud had a density of 18.3 pounds per gallon, a plastic viscosity of 30 cp, and a yield point of 10 lb/100 ft^2, when measured at a temperature of 150 ^oF. The bottom hole assembly consisted of 200 ft of 4.75-in drill collars having an internal diameter of 2.06 in. and 1300 ft of 3.5-in. heavy weight drill pipe also having a internal diameter of 2.06 in. The lower portion of the tapered drill pipe consisted of 3650 ft of 3.5-in drill pipe having an internal diameter of 2.764 in. The upper portion of drill pipe had an outside diameter of 5.00 in and an internal diameter of 4.276 in.

The well control event started while tripping out of the hole to replace the bit. After the drill string was returned to bottom, the drilling crew did not initially recognize the signs that an underground blowout was in progress and implemented the driller's method to circulate the well clean. However, the underground blowout was not recognized and the driller's method resulted in the bottom hole pressure being maintained at too low a value since a static (non-flowing) condition was not present when the pump was brought up to speed. (A discrepancy between the pre-recorded slow circulating rate and the pump pressure during the kill attempt was not recognized.) Gas was circulated up the annulus to a depth of about 12,900 ft before it became apparent that casing pressure was rising too quickly and that the well was still flowing on bottom. At this point, the well was shut-in to determine an appropriate course of action to bring the now recognized underground blowout under control. A review of the pressure records indicated that the fracture injection pressure at the suspected loss of circulation zone is equivalent to 18.6 pounds per gallon.

In this case, the entry and exit points were known through familiarity with the geology of the area. When the likely entry and exit point are unknown, temperature and or noise logs can be run inside the drill string to make this determination.

Use of the new program will be illustrated to determine if a Bullhead Kill Operation would likely result in the successful control of the suspected underground blowout situation. It was decided to fill the upper annulus with 18.6 pound per gallon mud by pumping down the casing and to fill the lower annulus with 18.7 pound per gallon mud by pumping down the drill string. The volume of 18.6 pound per gallon mud needed to fill the upper annulus to the depth of the exit point is about 700 barrels. The drill string capacity is about 250 barrels and the capacity of the lower annulus is about 50 barrels, requiring about 300 barrels of 18.7 pound per gallon mud to be pumped down the drill string to fill the drill string and the lower annulus. The required program input will now be presented for this example case.

Program Input

The input file is a text file that contains data identification information as well as the actual input data. It is recommended that a simple text editor such as Microsoft Notepad be used to edit the input file to reduce the chance of adding hidden characters to the file that could confuse the separation between input data fields. The program will disregard any line in the input file that has an asterisk in the first column. This allows the user to add optional input data identification information that will be helpful in reminding the user about the next information that is required by the program. Some descriptive information has already been added to the example input data file by the program authors. However, the program user can modify, add, or delete any line with an asterisk in Column 1 without affecting program execution.

Case Description

```
************************** INPUT DATA FILE *****************************
*                                                                      *
*                                                                      *
*             BULLHEAD WELL CONTROL SIMULATION PROGRAM                 *
*         Prepared Under MMS Contract 14-35-001-30749 (Task  6)        *
*             ATB                               1/2002                 *
*                                                                      *
*                 ***** GENERAL RUN DESCRIPTION *****                  *
*                                                                      *
* ENTER RUN DATE:                                                      *
* -------------------------------------------------------------------- *
  2/3/2002
* -------------------------------------------------------------------- *
*   RUNdate                                                            *
*                                                                      *
* ENTER ALPHANUMERIC CASE DESCRIPTION FOR OUTPUT IDENTIFICATION:       *
* -------------------------------------------------------------------- *
  Underground Blowout while Drilling - Bullhead Kill
* -------------------------------------------------------------------- *
```

The first two lines of input are alphanumeric information used to label the program output. Each line is limited to 70 characters of input. Information such as the date of the simulation, the date of the well control event, the well name, the well location, or the rig name could be entered.

Surface Piping Description

```
*                  ***** GEOMETRY DESCRIPTION *****                      *
*                                                                        *
* CHOKE\KILL LINE SURFACE PIPING: * DRILL-PIPE MANIFOLD SURFACE PIPING:*
* (PRESSURE GAUGE TO BOP)         * (PRESSURE GAUGE TO DRILLSTRING)    *
*                                 *                                    *
*                                 * (Enter zeros if not present)       *
*                                 *                                    *
*  EQUIVALENT  EQUIVALENT         *  EQUIVALENT  EQUIVALENT            *
*   DIAMETER    LENGTH    ROUGH.  *   DIAMETER     LENGTH    ROUGH.    *
*     (in)       (ft)      (in)   *     (in)        (ft)      (in)     *
* --------------------------------*----------------------------------- *
       3.52     50.0    0.00065         3.52       60.0       0.00065
* --------------------------------*----------------------------------- *
```

The equivalent diameter in inches, equivalent length in feet, and pipe roughness in inches for the surface piping between the pump and the well must be entered for casing and drillstring respectively. These six numerical inputs can be separated by one or more spaces or by a single comma.

Drill String Description

```
* MUD FILLED DRILL STRING OR WORK STRING DATA:                           *
*                                                                        *
* COMPLETE TABLE BELOW FOR EACH SEC OF DRILL STRING FLOW PATH HAVING     *
* A DIFFERENT SIZE: START AT TOP OF DRILL STRING (RKB) AND USE A         *
* MAXIMUM OF 20 SECTIONS.(Enter zero for Injection String OD if no       *
* string is inside drillpipe or work string. The measured depth to the  *
* bottom of the drillpipe or workstring must be at the well bottom.)     *
*                                                                        *
* EQ. DIAM CODE: 1= Based on Laminar Flow Theory                         *
*                2=Based on Hydraulic Radius Concept                     *
*                                                                        *
* MEASURED DEPTH TO  INJECTION                                           *
*  SECTION BOTTOM    STRING OD   PIPE ID   EQ. DIAM   ROUGHNESS          *
*      (FEET)        (INCHES)    (INCHES)   (CODE)    (INCHES)           *
* -------------------------------------------------------------------- *
       12150.         0.000       4.276       2      0.00065
       15800.         0.000       2.764       2      0.00065
       16700.         0.000       2.060       2      0.00065
       17300.         0.000       2.060       2      0.00065
* -------------------------------------------------------------------- *
```

A line of input must be entered for each section of drill string having a different size. Each line of table entry includes:

- The measured depth to the bottom of the section in feet;
- The outer diameter of any inner injection string (such as a coil tubing string) present inside of the drill string in inches. A zero is entered in this field if no inner injection string is present (usual situation);
- The internal diameter of the drill string or workstring;
- An integer code (no decimal point) of 1 if the equivalent diameter of the annulus between the drill string and an inner injection string is to be computed based on laminar flow theory or 2 if the hydraulic radius concept will be used. If no inner string is present, a value of 2 is required.
- The pipe roughness parameter, in inches. (A value of zero is for perfectly smooth pipe. A value of 0.00065 is often used for new mill pipe.)

Shown above are input data entries for the example Bullhead Kill analysis.

Drill String Restrictions

```
* MWD INPUT DATA                                                        *
* (ENTER 0.0 FOR DISCHARGE COEFFICIENT & TFA IF NO MWD IS PRESENT)      *
*                                                                       *
*             DISCHARGE       TOTAL FLOW AREA                           *
*            COEFFICIENT        (SQ. INCHES)                            *
* -------------------------------------------------------------------- *
                0.0               0.0
* -------------------------------------------------------------------- *
*                                                                       *
* MUD MOTOR INPUT DATA                                                  *
* (ENTER 0.0 FOR OFF-BOTTOM PRESSURE DROP IF NO MUD MOTOR IS PRESENT)   *
*                                                                       *
*            OFF-BOTTOM                                                 *
*           PRESSURE DROP                                               *
*              (PSIA)                                                   *
* -------------------------------------------------------------------- *
               0.0
* -------------------------------------------------------------------- *
*                                                                       *
* BIT INPUT DATA                                                        *
* (ENTER 0.0 FOR DISCHARGE COEFFICIENT & TFA IF NO BIT IS PRESENT)      *
*                                                                       *
*             DISCHARGE       TOTAL FLOW AREA                           *
*            COEFFICIENT        (SQ.INCHES)                             *
* -------------------------------------------------------------------- *
               0.95              0.35
* -------------------------------------------------------------------- *
```

Restrictions in the drill string that can cause additional pressure drops due to flow of mud include Measurement-While-Drilling (MWD) tools, Mud Motors, and Jet Bits. For well control operations, only the off-bottom pressure drop through the mud motor is needed. MWD tools and jet bits are modeled using a discharge coefficient and a total flow area. Nominal discharge coefficients are 0.9 for MWD tools and 0.95 for jet bits. When one or more of these components are not present, zeros should be entered in the appropriate fields for the missing components. All of these components are assumed to be present in the bottom cell of the drill string. The user should not force the program to use a small cell volume in an attempt to more accurately model short component of the bottom-hole assembly. Generally, it is best to model the entire drill collar assembly with a single cell of an average internal diameter in order to avoid creating a small cell.

Shown above are input data entries for the example Bullhead Kill analysis. Only a bit with a total flow area of 0.35 was present in the drill string.

Annular Flow Path Description

```
* ANNULAR FLOW PATH GEOMETRY                                                   *
*                                                                              *
*                                                                              *
* COMPLETE THE TABLE BELOW FOR EACH SECTION OF KICK FLOW PATH HAVING           *
* A DIFFERENT SIZE OR TO LOCATE FLOW EXIT: START AT SURFACE AND USE A          *
* MAXIMUM OF 20 SECTIONS) (If BOP Closed on Subsea Stack, Enter "0" for*
* Pipe OD and enter choke line ID for Casing or Hole ID. [Single line          *
* only] Identify depth of flow exit point to formation by placing a "1"*
* in table in "FLOW EXIT DEPTH?" column in row corresponding to exit           *
* depth and entering a "0" for all other depths. The total length of           *
* the kick flow path is the depth to the kicking formation.                    *
*                                                                              *
*  MEASURED  FLOW EXIT                                          INITIAL        *
*  DEPTH TO   DEPTH?              CASING OR  EQUIVALENT  FLUID IN SEC          *
* SEC BOTTOM  (YES=1    PIPE OD    HOLE ID    DIAMETER   (Mud=1,Gas=2          *
*   (FEET)    or NO=0) (INCHES)   (INCHES)      CODE       Water=3)            *
* -------------------------------------------------------------------- *
    12150.       0       5.000      8.525        2           1
    12900.       0       3.500      8.525        2           2
    14000.       0       3.500      6.765        2           2
    15600.       0       3.500      6.765        2           2
    15800.       1       3.500      6.500        2           2
    15900.       0       3.500      6.500        2           2
    16000.       0       3.500      6.500        2           2
    16100.       0       3.500      6.500        2           2
    16200.       0       3.500      6.500        2           2
    16300.       0       3.500      6.500        2           2
    16400.       0       3.500      6.500        2           2
    16500.       0       3.500      6.500        2           2
    16600.       0       3.500      6.500        2           2
    16700.       0       3.500      6.500        2           2
    16800.       0       3.500      6.500        2           2
    16900.       0       3.500      6.500        2           2
    17000.       0       3.500      6.500        2           2
    17100.       0       3.500      6.500        2           2
    17300.       0       4.750      6.500        2           2
* -------------------------------------------------------------------- *
```

A line of input must be entered for annular flow path section having a different size or to specify the exit point of the underground blowout. Additional lines of input can also be used to force a smaller grid in the lower annulus than in the upper annulus. Each line of table entry includes:

- The measured depth to the bottom of the section in feet (The last entry must correspond to the depth of the kicking formation);

- An integer code (no decimal point allowed) having a value of 0 for depth entries that are not the exit point of the underground blowout and a value of 1 for the exit point of the underground blowout. (The program can consider only a single exit point and will use the deepest one specified.) (The program is not designed to handle an exit point at the bottom of the well as would be the case in a Bullhead Kill during a well workover operation. as this was beyond the scope of the research task.)

- The outer diameter of the drill string in inches. A zero is entered in this field if no drill string is present in this section of the flow path, e.g. pumping down a choke line to a subsea Blowout Preventer Stack.

- The internal diameter of the section of the flow path, e.g. the casing or liner internal diameter or bore-hole diameter;

- An integer code (no decimal point) of 1 if the equivalent diameter of the annulus between the drill string and an inner injection string is to be computed based on laminar flow theory or 2 if the hydraulic radius concept will be used. If no inner string is present, a value of 2 is required.

- An integer code (no decimal point) of 1 if mud initially fills this section, a code of 2 if gas initially fills this section, or a code of 3 if water initially fills this section.

Shown above are input data entries for the example Bullhead Kill analysis. Note that below the exit point at 15,800 ft, 100-ft intervals are used except for the smaller capacity section opposite the drill collars. This was done to force a finer grid in the lower annulus. However, intervals of less than 100 ft are generally not recommended. (The output files "GEOM_A01.Txt" can be reviewed to see the resulting cell volume distribution.)

Directional Survey Table

```
* DIRECTIONAL SURVEY TABLE (Maximum of 200 entries)                     *
*                                                                       *
*     MEASURED DEPTH (RKB)       VERTICAL DEPTH (RKB)                   *
*           (FT)                       (FT)                             *
* ------------------------------------------------------------------- *
              0.0                         0.0
          12400.0                     12399.0
          16500.0                     16494.9
          16700.0                     16694.5
          17000.0                     16994.2
          17400.0                     17392.8
* ------------------------------------------------------------------- *
```

A directional survey table is required to determine vertical depth from measured depths. Each line of input consists of a measured depth in feet followed by the corresponding vertical depth in feet.

Mud Properties Table

```
*                      ***** MUD PROPERTIES *****                           *
*                                                                           *
* ENTER PROPERTIES OF MUD IN WELL AT TIME OF KICK AND                       *
* PROPERTIES OF MUDS USED TO REMOVE KICK FROM WELL (Maximum of 10):         *
* (VALUE ENTERED FOR WATER FRACTION MUST INCLUDE SWELLING DUE TO            *
* DISSOLVED SALTS).                                                         *
*                                                                           *
*  MUD        MUD    TEMP   PLASTIC   YIELD   WATER   WATER   OIL           *
* NUMBER    DENSITY        VISCOSITY  POINT   FRAC   DENSITY  FRAC          *
*            (PPG)   (oF)    (CP)   (#/100SF)         (PPG)                 *
* ------------------------------------------------------------------------- *
     1        18.3   150.0     30.0     10.0   0.630    8.50   0.01
     2        18.7   150.0     35.0     12.0   0.600    8.53   0.01
     3        18.6   150.0     32.0     12.1   0.600    8.53   0.01
* ------------------------------------------------------------------------- *
```

A line of input must be entered for each mud used in the Bullhead Kill Simulation. Mud Number 1 is assumed to be the old mud that is in the well when the underground blowout occurred. Not all muds listed in the table have to be used in a given Bullhead Kill Simulation. Each line in the mud table must contain:

- The mud number integer (no decimal points);
- The mud density in pounds per gallon;
- The reference temperature at which the plastic viscosity and yield point were measured in degrees Fahrenheit;
- The Plastic Viscosity of the mud in centipoise;
- The yield point of the mud in pounds per hundred square feet;
- The volume fraction of the mud that is composed of water;
- The density of the water phase of the mud; and
- The oil fraction of the mud.

If mud retort data are not available, the volume fraction of solids in the mud can be estimated from the mud density and Figure 5.4.

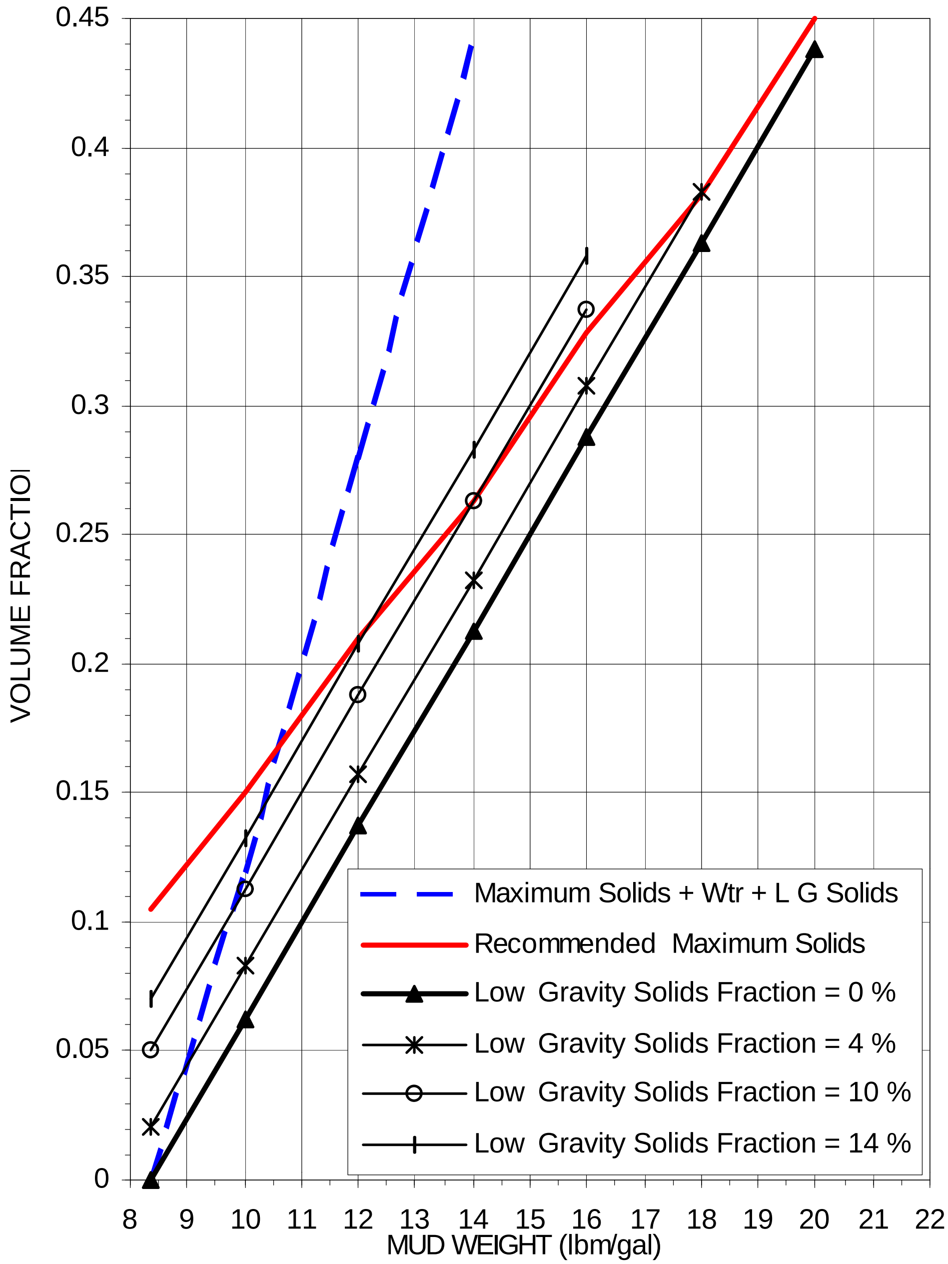

Figure 5.4 - Solids Fraction vs. Mud Density

Mud Rheological Model

```
* ENTER RHEOLOGICAL MODEL CODE                                          *
* 1= Bingham Plastic                                                    *
* 2= Power Law                                                          *
* -------------------------------------------------------------------- *
    1
* -------------------------------------------------------------------- *
```

Mud Rheology can be modeled either using a Bingham Plastic Model or a Power Law fluid model by entering an integer code (no decimal point) of either 1 or 2 respectively.

Mud Temperature Profile

```
* ENTER SURFACE MUD TEMPERATURE AND FLOWING TEMPERATURE GRADIENTS:     *
*                                                                       *
*      SUCTION PIT       FLOWLINE         ANNULAR                       *
*      TEMPERATURE     TEMPERATURE        GRADIENT                      *
*         (oF)            (oF)          (oF/100 ft)                     *
* -------------------------------------------------------------------- *
        125.0          130.0            0.71
* -------------------------------------------------------------------- *
```

The mud temperature profile during the Bullhead Kill operation is defined by entering the surface mud temperature in degrees Fahrenheit at the suction pit and at the flow line, and the average flowing temperature gradient in the annulus in degrees Fahrenheit per 100 ft. The flowing gradient in the drill pipe is chosen so that the temperature at the bit is the same as the annular temperature at that depth.

Properties of Upper Formation (Exit Point)

```
* UPPER FORMATION (WEAKEST ZONE)                                        *
*                                                                       *
*                            FRACTURE    FRACTURE     dP/dQ             *
*     FORMATION     PORE    INITIATION  PROPAGATION   SLOPE             *
*    TEMPERATURE  PRESSURE   PRESSURE    PRESSURE    (PSI/              *
*        (oF)     (lb/gal)   (lb/gal)    (lb/gal)    bbl/min)           *
* ------------------------------------------------------------------- *
        305.0       17.3        18.6        18.6        2.0
* ------------------------------------------------------------------- *
```

The upper formation is the zone that fractures and provides an exit point during the underground blowout. The formation properties that must be entered include:

- The formation temperature in degrees Fahrenheit;
- The pore pressure gradient of the formation expressed as an equivalent mud density in pounds per gallon;
- The fracture initiation pressure gradient, expressed as an equivalent mud density in pounds per gallon;
- The pressure gradient at which the fracture will propagate when pumping mud at 0.5 barrels per minute, expressed as an equivalent mud density in pounds per gallon; and
- The increase in fracture propagation pressure with increasing mud pump rate, expressed in units of pounds per square inch divided by barrels per minute.

Properties of Lower Formation (Kick Zone)

```
* LOWER FORMATION (KICK ZONE)                                          *
*                                                                      *
*   FORM  PORE   FORM  DRAIN  FORM  WAT  FORM    HOR   Kv/Kh  SKIN     *
*   TEMP  PRES   THICK  AREA  POR   SAT  COMP    PERM  RATIO           *
*   (oF)  (lb/   (FT)  (Acre)           (Micro   (MD)                  *
*          gal)                          Sips)                         *
* ---------------------------------------------------------------------*
  325.0   18.3   150.   500  .15   .17    5.0    50.0    .05    10.0
* ---------------------------------------------------------------------*
*                                                                      *
* Note WELL TYPE CODE:                                                 *
*     1 = Vertical or Directional Well                                 *
*     2 = Horizontal Well                                              *
*                                                                      *
*    WELL        AREAL   FORMATION    FORMATION    WATER/GAS           *
* PENETRATION    ASPECT    WATER         GAS         RATIO       WELL  *
*   LENGTH       RATIO   SPECIFIC     SPECIFIC      (BBL/        TYPE  *
*    (FT)                GRAVITY      GRAVITY       MMSCF)       CODE  *
* ---------------------------------------------------------------------*
     50.0         1       1.1          0.65          7.0         1
* ---------------------------------------------------------------------*
```

The lower formation is the zone that flows into the well and causes the underground blowout. The first line of formation properties that must be entered include:

- The formation temperature in degrees Fahrenheit;
- The pore pressure gradient of the formation expressed as an equivalent mud density in pounds per gallon;
- The vertical net gas-bearing formation thickness in feet;
- The reservoir drainage area in Acres;
- The average porosity entered as a fraction;
- The average water saturation entered as a fraction;
- The rock compressibility (pore volume basis) entered in microsips (10^{-06}/psi);
- The average horizontal permeability to gas in millidarcies;
- The average vertical permeability to horizontal permeability ratio expressed as a fraction; and
- The Skin factor resulting from exposure of the formation to drilling mud.

The second line of required input includes:

- The exposed length of open bore hole cut into or through the formation in feet (For a horizontal well, enter the length of the lateral);
- The areal aspect ratio of the formation in the plane perpendicular to the bore hole (See Figure 5.3);
- The specific gravity of the formation water;
- The specific gravity of the formation gas;
- The producing water to gas ratio in units of stock tank barrels per million standard cubic feet; and
- An integer code (no decimal point) of 1 if the well is a vertical or directional well and a code of 2 if the well is a horizontal well.

Base Conditions for Gas

```
*                                                                         *
*    TEMPERATURE    PRESSURE                                              *
*       BASE          BASE                                                *
*     (DEG F)        (PSIA)                                               *
* ----------------------------------------------------------------------- *
        60.0       15.025
* ----------------------------------------------------------------------- *
```

The reference base conditions for determining the gas volume in standard cubic feet. The mud gas separator is assumed to operate at base conditions when estimating fluid properties.

Depth Increment

```
* SPECIFY DEPTH INCREMENT IN FEET FOR CALCULATIONS:                       *
* (Total Measured Depth divided by Depth Increment cannot exceed 150      *
*  and Depth Increments of less than 100 feet are not recommended.        *
*                                                                         *
* ----------------------------------------------------------------------- *
        500.0
* ----------------------------------------------------------------------- *
```

The maximum section length in feet to be used in breaking the flow paths into discrete cells must be entered. The total measured depth of the well divided by 150 is the maximum value permitted for this parameter. A value of less than 100 feet is not recommended.

Optional Snapshot Codes

```
* SPECIFY DESIRED ADDITIONAL SNAPSHOT PROPERTIES ( 0 = NO   1 = YES )  *
*                                                                      *
* VELOCITY   VISCOSITY   DENSITY COMPRESSIBILITY  VOL.FRACION   FVF    *
* -------------------------------------------------------------------- *
      0         0          0         0               0          0
* -------------------------------------------------------------------- *
```

A number of optional parameters in the annular flow path can be obtained as program snapshot output in addition to the standard parameters. A snapshot provides the value of the parameters of interest in every discrete cell. Optional snapshots should be used only when specific supplementary information is needed that is not shown in the standard output. Snapshots should be used sparingly to avoid creating large numbers of output files each time the program is run. The supplemental snapshot files will be placed in the same file folder (subdirectory) as the input data file. The optional snapshot parameters include velocity, viscosity, density, compressibility, volume fraction, and formation volume factor. For each property, the value for mud, formation gas, formation water, and effective average value is given. For velocity, both the superficial phase velocities and the average phase velocities are given. The volume fraction snapshot also gives the volume fraction of old mud (mud 1) and new mud (mud 2) in each cell.

Mud Identification Codes

```
*   OLD        DP KILL     ANN KILL                                         *
*   MUD ID     MUD ID       MUD ID                                          *
*   (CODE)     (CODE)       (CODE)                                          *
* --------------------------------------------------------------------- *
      1           2            3
* --------------------------------------------------------------------- *
```

Three integer codes (no decimal points) must be entered. The first code identifies which mud in the mud properties table was in the well when the underground blowout occurred. The second integer code identifies which mud in the mud-properties table is being pumped down the drill pipe. The third integer code identifies which mud in the mud-properties table is being pumped down the casing. Not all muds in the mud-properties table have to be used in a given Bullhead Kill Simulation. The same mud code can be used more than once in entering the three mud identifications on this line.

Pump Operating Conditions

```
*  FILL OUT TABLES BELOW FOR OPERATING CONDITIONS DURING BULLHEAD KILL:*
*                                                                       *
* Note SNAPSHOT CODE:                                                   *
*    0= Do NOT enable snapshot for this time.                           *
*    1= Do enable snapshot for this time.                               *
*                                                                       *
*   SIM      SNAP        DP KILL       ANN KILL                         *
*   TIME     SHOT         RATE           RATE                           *
*   (MIN)   (CODE)      (GAL/MIN)     (GAL/MIN)                         *
* --------------------------------------------------------------------- *
      0.0      1         230.0          350.0
      1.0      1         230.0          350.0
     20.0      1         230.0          350.0
     40.0      1         230.0          350.0
     60.0      1         100.0          350.0
     80.0      0           0.0            0.0
* --------------------------------------------------------------------- *
```

A line of input is required for each time at which a change in pump rate is desired or a set of output snapshots are desired. Each line of input must contain:

- The reference time in minutes (The first line should be at zero time);
- An integer code (No decimal points) of 0 if no snapshots are desired for this time or 1 if snapshots are desired at this time;
- The pump rate down the drill pipe in gallons per minute; and

- The annular kill rate or pump rate down the casing in gallons per minute.

Program Output

Program output created for the example Bullhead Kill Operation is shown in the Appendix. The program results show that the Bullhead kill operation would be successful in pumping all formation fluids into the annulus and result in a dead well when the pumps are stopped.

The program output was used to create the plots shown in Figures 5.5-5.8. Note from Figure 5.5 that for this highly productive gas sand, the predicted underground blowout rate at the start of the kill is about 100 Million Standard Cubic Feet per Day. However, this feed rate drops rapidly once the Bullhead Kill Operation is started. As the formation is killed, an increase in pump pressure down the drill pipe is seen. The later reduction in pump pressure corresponds to heavier mud reaching the bit. Figures 5.7-5.8 show the expected casing pressure response as gas is forced down the casing and into the fracture.

For additional practice, the user may wish to modify the input to simulate blowing the jets out of the bit (or perforating the drill collars) before attempting the Bullhead Kill Operation to reduce the risk of plugging one or more jets during the kill. Since increasing pump pressure is the main surface indicator of success during the Bullhead Kill Operation, plugged jets could give a false indication of success.

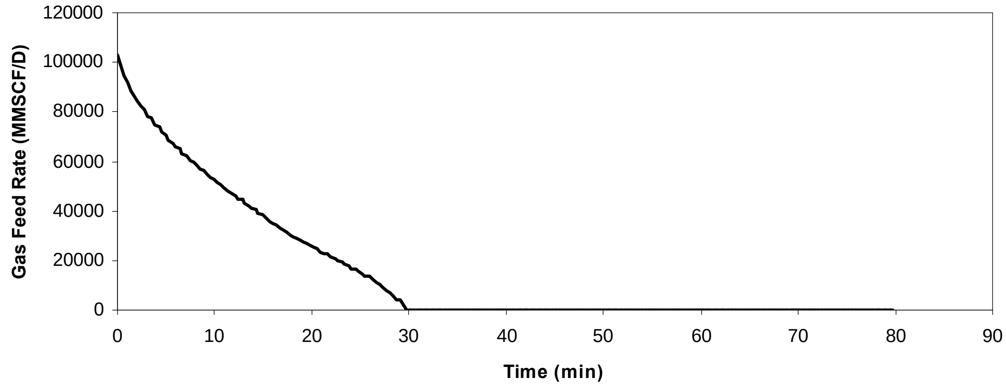

Figure 5.5 – Predicted Gas Feed Rate on Bottom (MMSCF/D)

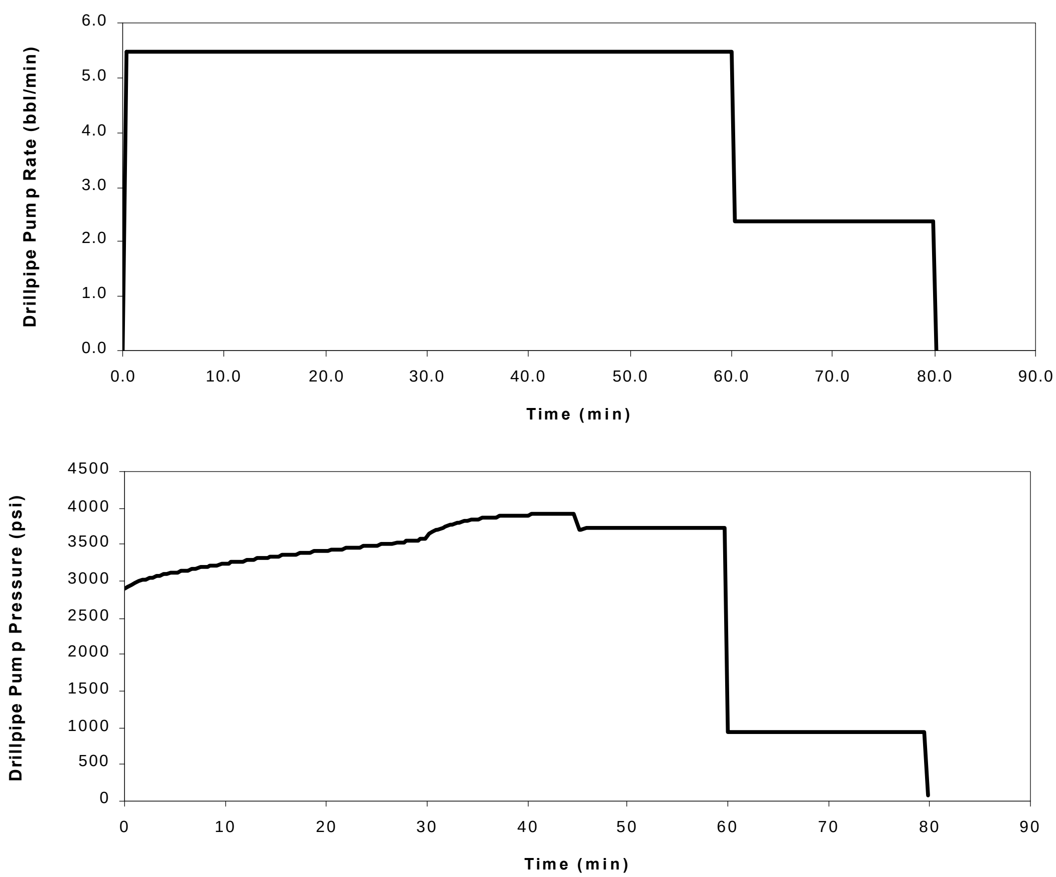

Figure 5. 6– Predicted Drill Pipe Pump Pressure for Specified Pump Rate Schedule

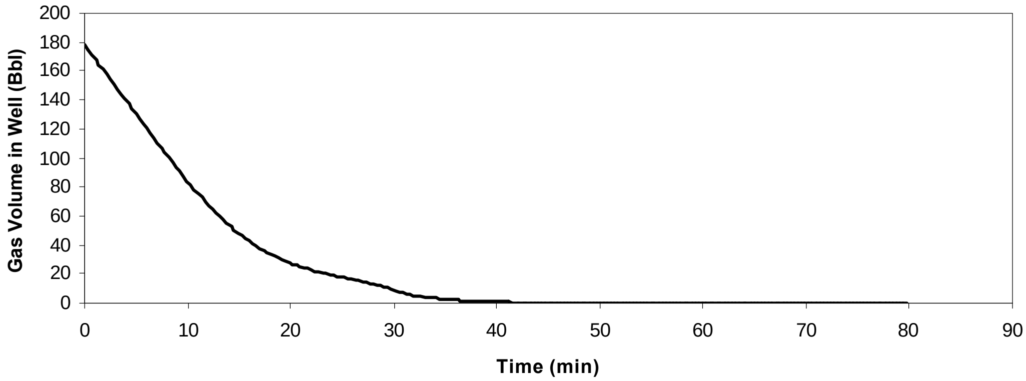

Figure 5.7 – Predicted Gas Volume in Well (Bbl)

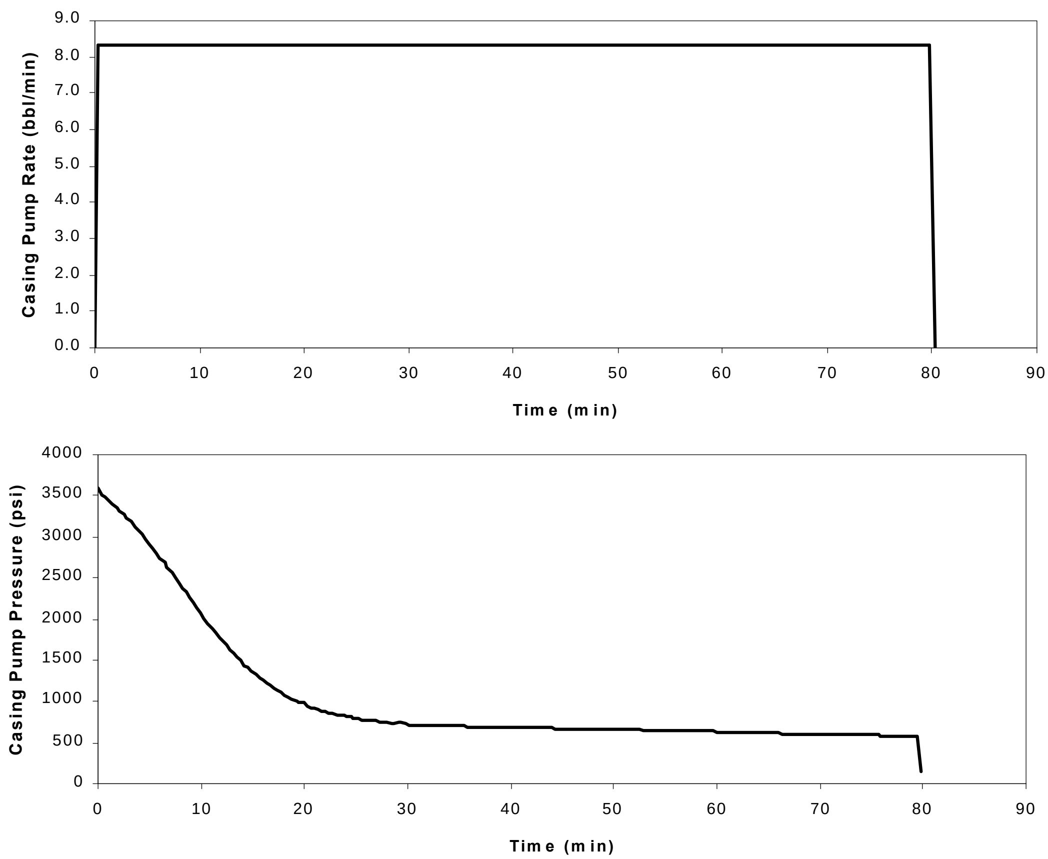

Figure 5. 8– Predicted Casing Pump Pressure for Specified Pump Rate Schedule

Chapter 6

Conclusions and Recommendations

Underground blowouts are a significant complication to well control operations. Remedial actions generally fall outside the normal procedure taught in a well control school that consists of filling out a standard kill sheet and circulating the well on a choke at a constant bottom hole pressure. In some cases, implementing the normal procedure can bring additional formation fluids into the casing and increase the surface casing pressure. This MMS sponsored research at LSU was directed at providing additional tools in the public domain for evaluating when Bullhead Kill Operations would have a high chance of success for controlling Underground Blowouts.

A major concern about the use of Bullhead Kill Operations when gas has moved a significant distance up the well is whether or not sufficient mud velocity can be achieved to efficiently push the gas back down the well. Little work has been done on countercurrent gas slip through non-Newtonian fluids in a large diameter annulus. An experimental study of Bullhead Kill Operations was conducted in a vertical well designed to simulate formation fracturing using a thief string of tubing. The primary focus of the research was the determination of countercurrent gas slip velocities. The experimental work in a research well was supplemented by experiments conducted in an inclined model of an annulus to determine the effect of vertical deviation on gas slip. A gas slip correlation was developed based on the experimental data and new public domain Bullhead Kill Software was developed which made use of the new correlation.

Conclusions

The following observations were made based on the experiments:

1. A full-scale downhole fracture simulator can be developed using data acquisition, including downhole pressure measurement, and computer control.
2. The removal efficiencies for bullheading increase linearly with increasing injection rate.
3. The removal efficiencies for mud were considerably higher than for water.
4. One experiment was run with an initial gas column height of half that used in the other experiments. The shortened gas column had minimal effect on removal efficiency.
5. New public domain software for modelling Bullhead Kill Operations for underground blowouts from gas wells has been developed and partially verified using the experimental data and some limited field data.
6. The new public domain software can be used to estimate the magnitude of an underground blowout from a gas reservoir when formation permeability and thickness is known.

7. The new public domain software can be used to predict the surface pressures to be expected during a given successful Bullhead Kill operation to provide assistance in evaluating a Bullhead Kill Operation in progress.

Recommendations

1. The next phase of this work should focus on more extensive verification of the new software using field data of bullhead kill operations for a wide variety of borehole geometries and drilling fluid properties.
2. A Workshop should be conducted for MMS personnel interested in learning to use the new sorfware to assist them in verifying the safety and suitability of proposed field operations in their district.

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Appendix

A

Example Program Output

Included in this appendix are output files that are generated when the example discussed in Chapter 5 is executed. The files are provided here to illustrate the type of output generated and to provide a ready reference to see if the program is operating correctly on the User's system when the example input data is processed. Electronic versions of these files are also available for download from MMS.

Listings of the following example output files are provided in this appendix: (Note that Error.txt is an output file generated by the example that is not shown in this appendix. Error.txt shows input data successfully processed without encountering an input error that stopped the program and any error messages generated during either a partial or completed execution if the input file.)

- INPUT.DAT – Input data file for example Bullhead Kill Analysis;

- GEOM_A01.TXT – Output file showing the geometry of the annular flow path and the subdivision of the flow path into discrete cells. Note that the depths shown are at the bottom of the cells.

- GEOM_P01.TXT – Output file showing the geometry of the drill pipe flow path and the subdivision of the flow path into discrete cells. Note that the depths shown are at the bottom of the cells.

- KILL_SUMMARY.TXT – Primary output file showing how key surface and subsurface parameters are predicted to vary with time during the simulated Bullhead Kill Operation.

- SNAP_A0X.TXT – Output showing value of key subsurface parameters for each discrete annular flow-path cell at the 4 times of interest specified in the input data file. Note that the depths and pressures shown are at the bottom of the cells and the fluid properties are average values used for the entire cell. Only the second snapshot (SNAP_A02.TXT) after the pumps have just started is shown.

- SNAP_P0X.TXT - Output showing value of key subsurface parameters for each discrete drill pipe flow-path cell at the 4 times of interest specified in the input data file. Note that the depths and pressures shown are at the bottom of the cells and the fluid properties are average values used for the entire cell. Only the second snapshot (SNAP_P02.TXT) after the pumps have just started is shown.

INPUT.DAT

```
************************* INPUT DATA FILE ****************************
*                                                                    *
*                                                                    *
*             BULLHEAD WELL CONTROL SIMULATION PROGRAM               *
*         Prepared Under MMS Contract 14-35-001-30749 (Task  6)      *
*             ATB                                 1/2002             *
*                                                                    *
*                 ***** GENERAL RUN DESCRIPTION *****                *
*                                                                    *
* ENTER RUN DATE:                                                    *
* ------------------------------------------------------------------ *
                              2/3/2002
* ------------------------------------------------------------------ *
*   RUNdate                                                          *
*                                                                    *
* ENTER ALPHANUMERIC CASE DESCRIPTION FOR OUTPUT IDENTIFICATION:     *
* ------------------------------------------------------------------ *
          Underground Blowout while Drilling - Bullhead Kill
* ------------------------------------------------------------------ *
*                                                                    *
*                                                                    *
*                   ***** GEOMETRY DESCRIPTION *****                 *
*                                                                    *
* CHOKE\KILL LINE SURFACE PIPING: * DRILL-PIPE MANIFOLD SURFACE PIPING:*
* (PRESSURE GAUGE TO BOP)         * (PRESSURE GAUGE TO DRILLSTRING)   *
*                                 *                                  *
*                                 * (Enter zeros if not present)     *
*                                 *                                  *
*  EQUIVALENT  EQUIVALENT         *  EQUIVALENT  EQUIVALENT          *
*   DIAMETER    LENGTH     ROUGH. *   DIAMETER     LENGTH     ROUGH.  *
*     (in)       (ft)       (in)  *     (in)        (ft)      (in)    *
* --------------------------------*--------------------------------- *
    3.52       50.0    0.00065       3.52       60.0       0.00065
* --------------------------------*--------------------------------- *
*  dman(2)     Lman(2)    eman(2)      dman(1)     Lman(1)   eman(1)  *
*                                                                    *
*                                                                    *
* MUD FILLED DRILL STRING OR WORK STRING DATA:                       *
*                                                                    *
* COMPLETE TABLE BELOW FOR EACH SECTION OF DRILL STRING FLOWPATH HAVING*
* A DIFFERENT SIZE: START AT TOP OF DRILL STRING (RKB) AND USE A     *
* MAXIMUM OF 20 SECTIONS.(Enter zero for Injection String OD if no   *
* string is inside drillpipe or work string.The measured depth to the  *
* bottom of the drillpipe or workstring must be at the well bottom.   *
*                                                                    *
* EQ. DIAM CODE: 1= Based on Laminar Flow Theory                     *
*               2=Based on Hydraulic Radius Concept                  *
*                                                                    *
* MEASURED DEPTH TO  INJECTION                                       *
*  SECTION BOTTOM    STRING OD   PIPE ID   EQ. DIAM   ROUGHNESS      *
*      (FEET)        (INCHES)    (INCHES)   (CODE)    (INCHES)       *
* ------------------------------------------------------------------ *
        12150.          0.000       4.276       2      0.00065
        15800.          0.000       2.764       2      0.00065
        16700.          0.000       2.060       2      0.00065
        17300.          0.000       2.060       2      0.00065
* ------------------------------------------------------------------ *
*    DEP(i,1)      dp1(i,1)   dp2(i,1)  Idep(i,1)    ep(i,1) [i=2,Ndps]*
* MWD INPUT DATA                                                     *
* (ENTER 0.0 FOR DISCHARGE COEFFICIENT & TFA IF NO MWD IS PRESENT)   *
*                                                                    *
*              DISCHARGE       TOTAL FLOW AREA                       *
*             COEFFICIENT       (SQ. INCHES)                         *
* ------------------------------------------------------------------ *
                       0.0                 0.0
* ------------------------------------------------------------------ *
*              CDmwd               Amwd                              *
*                                                                    *
* MUD MOTOR INPUT DATA                                               *
* (ENTER 0.0 FOR OFF-BOTTOM PRESSURE DROP IF NO MUD MOTOR IS PRESENT) *
*                                                                    *
*             OFF-BOTTOM                                             *
*            PRESSURE DROP                                           *
*               (PSIA)                                               *
* ------------------------------------------------------------------ *
                             0.0
* ------------------------------------------------------------------ *
*               dPmm                                                 *
*                                                                    *
* BIT INPUT DATA                                                     *
* (ENTER 0.0 FOR DISCHARGE COEFFICIENT & TFA IF NO BIT IS PRESENT)   *
*                                                                    *
*              DISCHARGE       TOTAL FLOW AREA                       *
*             COEFFICIENT       (SQ. INCHES)                         *
* ------------------------------------------------------------------ *
                      0.95                 0.35
* ------------------------------------------------------------------ *
*               CDbit              Abit                              *
*                                                                    *
* WELL GEOMETRY                                                      *
*                                                                    *
*                                                                    *
* COMPLETE THE TABLE BELOW FOR EACH SECTION OF KICK FLOW PATH HAVING  *
* A DIFFERENT SIZE OR TO LOCATE FLOW EXIT: START AT SURFACE AND USE A  *
* MAXIMUM OF 20 SECTIONS) (If BOP Closed on Subsea Stack, Enter "0" for*
* Pipe OD and enter choke line ID for Casing or Hole ID. [Single line  *
* only] Identify depth of flow exit point to formation by placing a "1"*
* in table in "FLOW EXIT DEPTH?" column in row corresponding to exit   *
* depth and entering a "0" for all other depths. The total length of   *
* the kick flow path is the depth to the kicking formation.          *
*                                                                    *
```

```
*  MEASURED  FLOW EXIT                                   INITIAL     *
*  DEPTH TO   DEPTH?              CASING OR  EQUIVALENT  FLUID IN SEC  *
* SEC BOTTOM  (YES=1    PIPE OD    HOLE ID    DIAMETER   (Mud=1,Gas=2  *
*   (FEET)    or NO=0) (INCHES)   (INCHES)     CODE       Water=3)    *
* ------------------------------------------------------------------ *
       12150.      0       5.000      8.535       2           1
       12900.      0       3.500      8.535       2           2
       14000.      0       3.500      6.750       2           2
       15600.      0       3.500      6.765       2           2
       15800.      1       3.500      6.500       2           2
       15900.      0       3.500      6.500       2           2
       16000.      0       3.500      6.500       2           2
       16100.      0       3.500      6.500       2           2
       16200.      0       3.500      6.500       2           2
       16300.      0       3.500      6.500       2           2
       16400.      0       3.500      6.500       2           2
       16500.      0       3.500      6.500       2           2
       16600.      0       3.500      6.500       2           2
       16700.      0       3.500      6.500       2           2
       16800.      0       3.500      6.500       2           2
       16900.      0       3.500      6.500       2           2
       17000.      0       3.500      6.500       2           2
       17100.      0       3.500      6.500       2           2
       17300.      0       4.750      6.500       2           2
* ------------------------------------------------------------------ *
*DEP(i,2),ExitLOC(i,2),dp1(i,2),dp2(i,2),Idep(i,2),IFcode(i,2),[i=2,Nas]
*                                                                    *
* DIRECTIONAL SURVEY TABLE (Maximum of 200 entries)                  *
*                                                                    *
*     MEASURED DEPTH (RKB)       VERTICAL DEPTH (RKB)                *
*            (FT)                       (FT)                         *
* ------------------------------------------------------------------ *
                  0.0                      0.0
              12400.0                  12399.0
              16400.0                  16395.3
              16500.0                  16494.9
              16600.0                  16594.6
              16700.0                  16694.5
              16800.0                  16794.4
              16900.0                  16894.4
              17000.0                  16994.2
              17100.0                  17094.0
              17200.0                  17193.0
              17300.0                  17293.0
              17400.0                  17393.0
* ------------------------------------------------------------------ *
*            Dmt(i)                    Dvt(i)             [i=1,NDmt]*
*                                                                    *
*                       ***** MUD PROPERTIES *****                   *
*                                                                    *
* ENTER PROPERTIES OF MUD IN WELL AT TIME OF KICK AND                *
* PROPERTIES OF MUDS USED TO REMOVE KICK FROM WELL (Maximum of 10):   *
* (VALUE ENTERED FOR WATER FRACTION MUST INCLUDE SWELLING DUE TO      *
* DISSOLVED SALTS).                                                  *
*                                                                    *
*  MUD       MUD    TEMP   PLASTIC   YIELD   WATER   WATER   OIL      *
* NUMBER   DENSITY         VISCOSITY  POINT   FRAC   DENSITY  FRAC     *
*           (PPG)   (oF)    (CP)   (#/100SF)          (PPG)           *
* ------------------------------------------------------------------ *
     1       18.3   150.0     30.0     10.0   0.610    8.50   0.01
     2       18.7   150.0     35.0     12.0   0.600    8.53   0.01
     3       18.6   150.0     32.0     12.1   0.600    8.53   0.01
* ------------------------------------------------------------------ *
*Imt(i),Wmmt(i),Tmt(i),PVmt(i),YPmt(i),Fwmt(i),Wwmt(i),Fomt(i)[i=1,Nmt]*
*                                                                    *
* ENTER RHEOLOGICAL MODEL CODE                                       *
* 1= Bingham Plastic                                                 *
* 2= Power Law                                                       *
* ------------------------------------------------------------------ *
                                  1
* ------------------------------------------------------------------ *
* Irel                                                               *
*                                                                    *
* ENTER SURFACE MUD TEMPERATURE AND FLOWING TEMPERATURE GRADIENTS:    *
*                                                                    *
*      SUCTION PIT       FLOWLINE         ANNULAR                    *
*      TEMPERATURE     TEMPERATURE        GRADIENT                   *
*         (oF)             (oF)          (oF/100 ft)                 *
* ------------------------------------------------------------------ *
              125.0           130.0            0.71
* ------------------------------------------------------------------ *
*       Tsur(1)         Tsur(2)         Tgrad(2)                     *
*                                                                    *
*                 ***** FORMATION PROPERTIES *****                   *
*                                                                    *
* UPPER FORMATION (WEAKEST ZONE)                                     *
*                                                                    *
*                            FRACTURE    FRACTURE     dP/dQ          *
*      FORMATION     PORE    INITIATION  PROPAGATION   SLOPE          *
*     TEMPERATURE  PRESSURE   PRESSURE    PRESSURE    (PSI/          *
*         (oF)     (lb/gal)   (lb/gal)    (lb/gal)    bbl/min)       *
* ------------------------------------------------------------------ *
          305.0       17.3        18.6        18.6        2.0
* ------------------------------------------------------------------ *
*        Tfu         Ppgfu       Pfgi        Pfgp        dPdQ        *
*                                                                    *
* LOWER FORMATION (KICK ZONE)                                        *
*                                                                    *
*   FORM  PORE   FORM  DRAIN  FORM  WAT  FORM    HOR   Kv/Kh  SKIN    *
*   TEMP  PRES   THICK  AREA  POR   SAT  COMP    PERM  RATIO          *
*   (oF)  (lb/   (FT)  (Acre)             (Micro  (MD)                *
*          gal)                            Sips)                      *
* ------------------------------------------------------------------*
   325.0   18.3   150.   500  .15   .17    5.0    50.0    .05    10.0
* ------------------------------------------------------------------*
*  Tfl     Ppgfl  Hfl    Afl   POR   Sw    Cfl    Kh      KvKh    Sfl  *
```

```
*                                                                       *
* Note WELL TYPE CODE:                                                  *
*     1 = Vertical or Directional Well                                  *
*     2 = Horizontal Well                                               *
*                                                                       *
*                                                                       *
*    WELL        AREAL   FORMATION    FORMATION    WATER/GAS            *
* PENETRATION    ASPECT    WATER        GAS          RATIO       WELL   *
*   LENGTH       RATIO   SPECIFIC     SPECIFIC      (BBL/        TYPE   *
*    (FT)                GRAVITY      GRAVITY       MMSCF)       CODE   *
* ----------------------------------------------------------------------*
     50.0         1       1.1          0.65          7.0         1
* ----------------------------------------------------------------------*
*   Lwfl         XY       SGw          SGg           WGR         Idw    *
*                                                                       *
*                                                                       *
*              ***** BASE AND SEPARATOR CONDITIONS *****                *
*                                                                       *
* SPECIFY BASE CONDITIONS                                               *
*                                                                       *
*    TEMPERATURE    PRESSURE                                            *
*       BASE          BASE                                              *
*     (DEG F)        (PSIA)                                             *
* --------------------------------------------------------------------- *
        60.0       15.025
* --------------------------------------------------------------------- *
*        Tb           Pb                                                *
*                                                                       *
*              ***** OUTPUT OPTION SPECIFICATIONS *****                 *
*                                                                       *
*                                                                       *
* SPECIFY DEPTH INCREMENT IN FEET FOR CALCULATIONS:                     *
* (Total Measured Depth divided by Depth Increment cannot exceed 150    *
*  and Depth Increments of less than 100 feet are not recommended.      *
*                                                                       *
* --------------------------------------------------------------------- *
        500.0
* --------------------------------------------------------------------- *
*        DepthINC                                                       *
*                                                                       *
*                                                                       *
*
* SPECIFY DESIRED ADDITIONAL SNAPSHOT PROPERTIES ( 0 = NO   1 = YES )  *
*                                                                       *
* VELOCITY   VISCOSITY   DENSITY COMPRESSIBILITY  VOL.FRACION   FVF     *
* --------------------------------------------------------------------- *
       0         0          0         0               0          0
* --------------------------------------------------------------------- *
*     Vflg      Uflg       Wflg      Cflg            Fflg      Mflg     *
*                                                                       *
* ADDITIONAL ANNULAR PRESSURE PREDICTION POINTS:                        *
*                                                                       *
*                                                                       *
*     ***** WELL CONTROL OPERATING CONDITION: BULLHEAD KILL *****       *
*                                                                       *
*   OLD        DP KILL     ANN KILL                                     *
*   MUD ID     MUD ID       MUD ID                                      *
*   (CODE)     (CODE)       (CODE)                                      *
* --------------------------------------------------------------------- *
      1           2            3
* --------------------------------------------------------------------- *
*   ImudOLD    ImudDP        ImudC                                      *
*                                                                       *
*                                                                       *
*  FILL OUT TABLES BELOW FOR OPERATING CONDITIONS DURING BULLHEAD KILL:*
*                                                                       *
* Note SNAPSHOT CODE:                                                   *
*    0= Do NOT enable snapshot for this time.                           *
*    1= Do enable snapshot for this time.                               *
*                                                                       *
*   SIM      SNAP        DP KILL       ANN KILL                         *
*   TIME     SHOT         RATE          RATE                            *
*   (MIN)   (CODE)      (GAL/MIN)     (GAL/MIN)                         *
* --------------------------------------------------------------------- *
      0.0      1         230.0          350.0
      1.0      1         230.0          350.0
     20.0      1         230.0          350.0
     40.0      1         230.0          350.0
     60.0      0         100.0          350.0
     80.0      0           0.0            0.0
* --------------------------------------------------------------------- *
*  TimeT(i)  Isnapt(i)  QtDP(i)      QtC(i)                [i=1,NTt]  *
*                                                                       *
************************** END OF DATA *********************************
```

GEOM_A01. TXT

INITIAL ANNULAR MODULE

No	Depth ft	TVD ft	Angle Deg	Inj_OD in.	Sec_ID in.	Eq Dia in.	Rough in.	Length ft	CapFac bbl/ft	Cap bbl	Cap_UP bbl	Cap_DN bbl	Nline
1	0.	0.	90.00	.000	3.520	3.520	.00065	50.	.01204	.60	744.71	.60	1.
2	500.	500.	.73	5.000	8.535	3.535	.00000	500.	.04648	23.24	744.11	23.84	1.
3	1000.	1000.	.73	5.000	8.535	3.535	.00000	500.	.04648	23.24	720.87	47.08	1.
4	1500.	1500.	.73	5.000	8.535	3.535	.00000	500.	.04648	23.24	697.63	70.32	1.
5	2000.	2000.	.73	5.000	8.535	3.535	.00000	500.	.04648	23.24	674.39	93.56	1.
6	2500.	2500.	.73	5.000	8.535	3.535	.00000	500.	.04648	23.24	651.15	116.80	1.
7	3000.	3000.	.73	5.000	8.535	3.535	.00000	500.	.04648	23.24	627.91	140.04	1.
8	3500.	3500.	.73	5.000	8.535	3.535	.00000	500.	.04648	23.24	604.67	163.28	1.
9	4000.	4000.	.73	5.000	8.535	3.535	.00000	500.	.04648	23.24	581.43	186.52	1.
10	4500.	4500.	.73	5.000	8.535	3.535	.00000	500.	.04648	23.24	558.19	209.76	1.
11	5000.	5000.	.73	5.000	8.535	3.535	.00000	500.	.04648	23.24	534.95	233.00	1.
12	5500.	5500.	.73	5.000	8.535	3.535	.00000	500.	.04648	23.24	511.71	256.24	1.
13	6000.	6000.	.73	5.000	8.535	3.535	.00000	500.	.04648	23.24	488.47	279.48	1.
14	6500.	6499.	.73	5.000	8.535	3.535	.00000	500.	.04648	23.24	465.23	302.72	1.
15	7000.	6999.	.73	5.000	8.535	3.535	.00000	500.	.04648	23.24	441.99	325.96	1.
16	7500.	7499.	.73	5.000	8.535	3.535	.00000	500.	.04648	23.24	418.75	349.20	1.
17	8000.	7999.	.73	5.000	8.535	3.535	.00000	500.	.04648	23.24	395.51	372.44	1.
18	8500.	8499.	.73	5.000	8.535	3.535	.00000	500.	.04648	23.24	372.27	395.68	1.
19	9000.	8999.	.73	5.000	8.535	3.535	.00000	500.	.04648	23.24	349.03	418.92	1.
20	9500.	9499.	.73	5.000	8.535	3.535	.00000	500.	.04648	23.24	325.79	442.16	1.
21	10000.	9999.	.73	5.000	8.535	3.535	.00000	500.	.04648	23.24	302.55	465.40	1.
22	10500.	10499.	.73	5.000	8.535	3.535	.00000	500.	.04648	23.24	279.31	488.64	1.
23	11000.	10999.	.73	5.000	8.535	3.535	.00000	500.	.04648	23.24	256.07	511.88	1.
24	11500.	11499.	.73	5.000	8.535	3.535	.00000	500.	.04648	23.24	232.83	535.12	1.
25	12150.	12149.	.72	5.000	8.535	3.535	.00000	650.	.04648	30.21	209.59	565.33	1.
26	12650.	12649.	1.82	3.500	8.535	5.035	.00000	500.	.05887	29.43	179.38	594.76	1.
27	12900.	12899.	2.47	3.500	8.535	5.035	.00000	250.	.05887	14.72	149.95	609.48	1.
28	13400.	13398.	2.46	3.500	6.750	3.250	.00000	500.	.03236	16.18	135.23	625.66	1.
29	14000.	13998.	2.46	3.500	6.750	3.250	.00000	600.	.03236	19.42	119.05	645.08	1.
30	14500.	14497.	2.47	3.500	6.765	3.265	.00000	500.	.03256	16.28	99.63	661.36	1.
31	15000.	14997.	2.46	3.500	6.765	3.265	.00000	500.	.03256	16.28	83.35	677.63	1.
32	15600.	15596.	2.46	3.500	6.765	3.265	.00000	600.	.03256	19.53	67.07	697.17	1.
33	15800.	15796.	2.47	3.500	6.500	3.000	.00000	200.	.02914	5.83	47.54	703.00	1.
34	15900.	15896.	2.46	3.500	6.500	3.000	.00000	100.	.02914	2.91	41.71	705.91	1.
35	16000.	15996.	2.47	3.500	6.500	3.000	.00000	100.	.02914	2.91	38.80	708.83	1.
36	16100.	16096.	2.47	3.500	6.500	3.000	.00000	100.	.02914	2.91	35.88	711.74	1.
37	16200.	16195.	2.47	3.500	6.500	3.000	.00000	100.	.02914	2.91	32.97	714.66	1.
38	16300.	16295.	2.46	3.500	6.500	3.000	.00000	100.	.02914	2.91	30.05	717.57	1.
39	16400.	16395.	2.47	3.500	6.500	3.000	.00000	100.	.02914	2.91	27.14	720.48	1.
40	16500.	16495.	5.13	3.500	6.500	3.000	.00000	100.	.02914	2.91	24.23	723.40	1.
41	16600.	16595.	4.45	3.500	6.500	3.000	.00000	100.	.02914	2.91	21.31	726.31	1.
42	16700.	16695.	2.56	3.500	6.500	3.000	.00000	100.	.02914	2.91	18.40	729.23	1.
43	16800.	16794.	2.56	3.500	6.500	3.000	.00000	100.	.02914	2.91	15.48	732.14	1.
44	16900.	16894.	.00	3.500	6.500	3.000	.00000	100.	.02914	2.91	12.57	735.06	1.
45	17000.	16994.	3.63	3.500	6.500	3.000	.00000	100.	.02914	2.91	9.65	737.97	1.
46	17100.	17094.	3.62	3.500	6.500	3.000	.00000	100.	.02914	2.91	6.74	740.88	1.
47	17300.	17293.	5.73	4.750	6.500	1.750	.00000	200.	.01913	3.83	3.83	744.71	1.

GEOM_P01. TXT

INITIAL DRILLSTRING MODULE

No	Depth ft	TVD ft	Angle Deg	Inj_OD in.	Sec_ID in.	Eq Dia in.	Rough in.	Length ft	CapFac bbl/ft	Cap bbl	Cap_UP bbl	Cap_DN bbl	Nline
1	0.	0.	90.00	.000	3.520	3.520	.00065	60.	.01204	.72	249.80	.72	1.
2	500.	500.	.73	.000	4.276	4.276	.00065	500.	.01776	8.88	249.08	9.60	1.
3	1000.	1000.	.73	.000	4.276	4.276	.00065	500.	.01776	8.88	240.20	18.48	1.
4	1500.	1500.	.73	.000	4.276	4.276	.00065	500.	.01776	8.88	231.32	27.37	1.
5	2000.	2000.	.73	.000	4.276	4.276	.00065	500.	.01776	8.88	222.44	36.25	1.
6	2500.	2500.	.73	.000	4.276	4.276	.00065	500.	.01776	8.88	213.56	45.13	1.
7	3000.	3000.	.73	.000	4.276	4.276	.00065	500.	.01776	8.88	204.68	54.01	1.
8	3500.	3500.	.73	.000	4.276	4.276	.00065	500.	.01776	8.88	195.79	62.89	1.
9	4000.	4000.	.73	.000	4.276	4.276	.00065	500.	.01776	8.88	186.91	71.77	1.
10	4500.	4500.	.73	.000	4.276	4.276	.00065	500.	.01776	8.88	178.03	80.65	1.
11	5000.	5000.	.73	.000	4.276	4.276	.00065	500.	.01776	8.88	169.15	89.53	1.
12	5500.	5500.	.73	.000	4.276	4.276	.00065	500.	.01776	8.88	160.27	98.41	1.
13	6000.	6000.	.73	.000	4.276	4.276	.00065	500.	.01776	8.88	151.39	107.29	1.
14	6500.	6499.	.73	.000	4.276	4.276	.00065	500.	.01776	8.88	142.51	116.18	1.
15	7000.	6999.	.73	.000	4.276	4.276	.00065	500.	.01776	8.88	133.63	125.06	1.
16	7500.	7499.	.73	.000	4.276	4.276	.00065	500.	.01776	8.88	124.75	133.94	1.
17	8000.	7999.	.73	.000	4.276	4.276	.00065	500.	.01776	8.88	115.87	142.82	1.
18	8500.	8499.	.73	.000	4.276	4.276	.00065	500.	.01776	8.88	106.98	151.70	1.
19	9000.	8999.	.73	.000	4.276	4.276	.00065	500.	.01776	8.88	98.10	160.58	1.
20	9500.	9499.	.73	.000	4.276	4.276	.00065	500.	.01776	8.88	89.22	169.46	1.
21	10000.	9999.	.73	.000	4.276	4.276	.00065	500.	.01776	8.88	80.34	178.34	1.
22	10500.	10499.	.73	.000	4.276	4.276	.00065	500.	.01776	8.88	71.46	187.22	1.
23	11000.	10999.	.73	.000	4.276	4.276	.00065	500.	.01776	8.88	62.58	196.10	1.
24	11500.	11499.	.73	.000	4.276	4.276	.00065	500.	.01776	8.88	53.70	204.98	1.
25	12150.	12149.	.72	.000	4.276	4.276	.00065	650.	.01776	11.55	44.82	216.53	1.
26	12650.	12649.	1.82	.000	2.764	2.764	.00065	500.	.00742	3.71	33.27	220.24	1.
27	13150.	13148.	2.46	.000	2.764	2.764	.00065	500.	.00742	3.71	29.56	223.95	1.
28	13650.	13648.	2.47	.000	2.764	2.764	.00065	500.	.00742	3.71	25.85	227.66	1.
29	14150.	14147.	2.46	.000	2.764	2.764	.00065	500.	.00742	3.71	22.14	231.37	1.
30	14650.	14647.	2.47	.000	2.764	2.764	.00065	500.	.00742	3.71	18.43	235.08	1.
31	15150.	15146.	2.46	.000	2.764	2.764	.00065	500.	.00742	3.71	14.72	238.79	1.
32	15800.	15796.	2.47	.000	2.764	2.764	.00065	650.	.00742	4.82	11.01	243.62	1.
33	16300.	16295.	2.46	.000	2.060	2.060	.00065	500.	.00412	2.06	6.18	245.68	1.
34	16700.	16695.	3.83	.000	2.060	2.060	.00065	400.	.00412	1.65	4.12	247.33	1.
35	17300.	17293.	4.05	.000	2.060	2.060	.00065	600.	.00412	2.47	2.47	249.80	1.

```
Off-Bottom Mud Motor Pressure Drop =      0. psi
Discharge Coefficient of MWD Tool  =    .000
Effective Total Flow Area of MWD   =  .00000 in2
Discharge Coefficient of Jet Bit   =    .950
Effective Total Flow Area of Bit   =  .35000 in2
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KILL_SUMMARY. TXT

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  2/3/2002
  Underground Blowout while Drilling - Bullhead Kill

 SIMULATED RESULTS:

-------------------------------------------------------------------------------------------------------------------------------
!       !                         !                         !           !           !           !                    !                   !
! TIME  ! PUMP NO.1 (DRILLPIPE)   ! PUMP NO.2   (CASING)    ! SURFACE   ! PRESSURE  ! BOTTOM    ! FORMATION FEED RATE ! KICK VOL IN WELL  !
!       !                         !                         !  CASING   ! AT EXIT   !  HOLE     !                    !                   !
!       ! RATE  VOLUME PRESSURE   ! RATE  VOLUME PRESSURE   !PRESSURE   !  POINT    !PRESSURE   !    GAS      WATER  !  GAS  WATER  Eff  !
! (min) ! (bpm) (bbl)     (psi)   ! (bpm) (bbl)     (psi)   !  (psi)    !  (psi)    !  (psi)    !  (mscf/d)  (bbl/d) ! (bbl) (bbl)  (%)  !
!       !                         !                         !           !           !           !                    !                   !

!    .0!  .00     .0     15.  !   .00     .0    3240. !   3240.  !   15282. !   15723. !  109250.2   764.8  ! 178.7     .6    .0!
!    .4! 5.48    1.9   2902.  !  8.33    3.0    3601. !   3536.  !   15309. !   15765. !  103088.4   721.6  ! 178.5     .6   -.3!
!    .7! 5.48    3.9   2933.  !  8.33    5.9    3517. !   3506.  !   15309. !   15795. !   98607.7   690.3  ! 175.0     .6   2.0!
!   1.1! 5.48    5.8   2959.  !  8.33    8.9    3483. !   3471.  !   15309. !   15822. !   94682.0   662.8  ! 171.5     .6   4.2!
!   1.4! 5.48    7.8   2977.  !  8.33   11.8    3439. !   3427.  !   15309. !   15841. !   91882.3   643.2  ! 168.0     .6   6.4!
!   1.8! 5.48    9.7   3000.  !  8.33   14.8    3407. !   3395.  !   15309. !   15863. !   88519.5   619.6  ! 164.6     .6   8.7!
!   2.1! 5.48   11.7   3015.  !  8.33   17.7    3366. !   3354.  !   15309. !   15878. !   86275.0   603.9  ! 161.2     .6  10.9!
!   2.5! 5.48   13.6   3030.  !  8.33   20.7    3325. !   3313.  !   15309. !   15894. !   84030.4   588.2  ! 157.8     .6  13.1!
!   2.8! 5.48   15.5   3041.  !  8.33   23.7    3277. !   3265.  !   15309. !   15905. !   82348.9   576.4  ! 154.4     .6  15.3!
!   3.2! 5.48   17.5   3052.  !  8.33   26.6    3230. !   3218.  !   15309. !   15916. !   80667.4   564.7  ! 151.0     .6  17.6!
!   3.5! 5.48   19.4   3067.  !  8.33   29.6    3188. !   3175.  !   15309. !   15932. !   78430.6   549.0  ! 147.6     .6  19.8!
!   3.9! 5.48   21.4   3075.  !  8.33   32.5    3132. !   3119.  !   15309. !   15939. !   77304.3   541.1  ! 144.2     .6  22.0!
!   4.3! 5.48   23.3   3090.  !  8.33   35.5    3087. !   3075.  !   15309. !   15954. !   75067.5   525.5  ! 140.8     .6  24.2!
!   4.6! 5.48   25.3   3097.  !  8.33   38.4    3030. !   3018.  !   15309. !   15962. !   73949.0   517.6  ! 137.4     .6  26.5!
!   5.0! 5.48   27.2   3112.  !  8.33   41.4    2982. !   2970.  !   15309. !   15977. !   71704.2   501.9  ! 133.9     .6  28.7!
!   5.3! 5.48   29.1   3120.  !  8.33   44.3    2919. !   2907.  !   15309. !   15985. !   70585.8   494.1  ! 130.5     .6  30.9!
!   5.7! 5.48   31.1   3131.  !  8.33   47.3    2864. !   2852.  !   15309. !   15996. !   68904.1   482.3  ! 127.1     .6  33.1!
!   6.0! 5.48   33.0   3142.  !  8.33   50.3    2809. !   2797.  !   15309. !   16007. !   67222.4   470.6  ! 123.7     .6  35.3!
!   6.4! 5.48   35.0   3150.  !  8.33   53.2    2746. !   2734.  !   15309. !   16015. !   66104.0   462.7  ! 120.4     .6  37.5!
!   6.7! 5.48   36.9   3157.  !  8.33   56.2    2685. !   2673.  !   15309. !   16023. !   64977.5   454.8  ! 117.0     .6  39.7!
!   7.1! 5.48   38.9   3168.  !  8.33   59.1    2630. !   2618.  !   15309. !   16034. !   63295.8   443.1  ! 113.6     .6  41.9!
!   7.5! 5.48   40.8   3176.  !  8.33   62.1    2568. !   2556.  !   15309. !   16042. !   62177.3   435.2  ! 110.3     .6  44.1!
!   7.8! 5.48   42.7   3187.  !  8.33   65.0    2512. !   2500.  !   15309. !   16053. !   60495.5   423.5  ! 106.9     .6  46.2!
!   8.2! 5.48   44.7   3195.  !  8.33   68.0    2449. !   2437.  !   15309. !   16061. !   59377.0   415.6  ! 103.6     .6  48.4!
!   8.5! 5.48   46.6   3202.  !  8.33   71.0    2385. !   2373.  !   15309. !   16068. !   58258.4   407.8  ! 100.3     .6  50.5!
!   8.9! 5.48   48.6   3210.  !  8.33   73.9    2322. !   2310.  !   15309. !   16076. !   57131.9   399.9  !  97.0     .6  52.6!
!   9.2! 5.48   50.5   3217.  !  8.33   76.9    2260. !   2248.  !   15309. !   16083. !   56013.4   392.1  !  93.8     .6  54.7!
!   9.6! 5.48   52.5   3225.  !  8.33   79.8    2199. !   2187.  !   15309. !   16091. !   54894.8   384.3  !  90.6     .6  56.7!
!   9.9! 5.48   54.4   3232.  !  8.33   82.8    2139. !   2126.  !   15309. !   16099. !   53768.3   376.4  !  87.4     .7  58.8!
!  10.3! 5.48   56.3   3240.  !  8.33   85.7    2071. !   2059.  !   15309. !   16106. !   52649.7   368.5  !  84.4     .7  60.8!
!  10.6! 5.48   58.3   3247.  !  8.33   88.7    2013. !   2000.  !   15309. !   16114. !   51531.1   360.7  !  81.3     .7  62.7!
!  11.0! 5.48   60.2   3255.  !  8.33   91.7    1949. !   1936.  !   15309. !   16121. !   50412.4   352.9  !  78.3     .7  64.6!
!  11.4! 5.48   62.2   3262.  !  8.33   94.6    1893. !   1881.  !   15309. !   16129. !   49285.9   345.0  !  75.4     .7  66.4!
!  11.7! 5.48   64.1   3270.  !  8.33   97.6    1838. !   1826.  !   15309. !   16136. !   48167.3   337.2  !  72.6     .7  68.2!
!  12.1! 5.48   66.1   3277.  !  8.33  100.5    1785. !   1773.  !   15309. !   16144. !   47048.6   329.3  !  69.8     .7  70.0!
!  12.4! 5.48   68.0   3285.  !  8.33  103.5    1734. !   1721.  !   15309. !   16152. !   45930.0   321.5  !  67.1     .7  71.7!
!  12.8! 5.48   69.9   3292.  !  8.33  106.4    1684. !   1672.  !   15309. !   16159. !   44803.4   313.6  !  64.4     .7  73.3!
!  13.1! 5.48   71.9   3296.  !  8.33  109.4    1629. !   1616.  !   15309. !   16163. !   44248.0   309.7  !  61.9     .7  74.9!
!  13.5! 5.48   73.8   3303.  !  8.33  112.3    1583. !   1570.  !   15309. !   16171. !   43129.3   301.9  !  59.4     .7  76.4!
!  13.8! 5.48   75.8   3311.  !  8.33  115.3    1530. !   1517.  !   15309. !   16178. !   42002.7   294.0  !  57.0     .7  77.9!
!  14.2! 5.48   77.7   3318.  !  8.33  118.3    1488. !   1475.  !   15309. !   16186. !   40884.0   286.2  !  54.7     .7  79.2!
!  14.5! 5.48   79.7   3322.  !  8.33  121.2    1440. !   1428.  !   15309. !   16190. !   40320.7   282.2  !  52.5     .7  80.6!
!  14.9! 5.48   81.6   3329.  !  8.33  124.2    1402. !   1390.  !   15309. !   16197. !   39202.0   274.4  !  50.4     .7  81.9!
!  15.3! 5.48   83.5   3337.  !  8.33  127.1    1365. !   1353.  !   15309. !   16205. !   38083.3   266.6  !  48.3     .7  83.1!
!  15.6! 5.48   85.5   3344.  !  8.33  130.1    1331. !   1319.  !   15309. !   16212. !   36964.5   258.8  !  46.3     .7  84.2!
!  16.0! 5.48   87.4   3352.  !  8.33  133.0    1291. !   1279.  !   15309. !   16220. !   35837.9   250.9  !  44.4     .7  85.3!
!  16.3! 5.48   89.4   3359.  !  8.33  136.0    1261. !   1249.  !   15309. !   16228. !   34719.1   243.0  !  42.6     .7  86.4!
!  16.7! 5.48   91.3   3363.  !  8.33  139.0    1225. !   1213.  !   15309. !   16231. !   34163.7   239.1  !  40.9     .7  87.4!
!  17.0! 5.48   93.3   3371.  !  8.33  141.9    1199. !   1187.  !   15309. !   16239. !   33037.0   231.3  !  39.2     .7  88.3!
!  17.4! 5.48   95.2   3374.  !  8.33  144.9    1163. !   1151.  !   15309. !   16243. !   32481.6   227.4  !  37.6     .7  89.2!
!  17.7! 5.48   97.1   3382.  !  8.33  147.8    1139. !   1126.  !   15309. !   16250. !   31362.8   219.5  !  36.1     .7  90.1!
!  18.1! 5.48   99.1   3389.  !  8.33  150.8    1110. !   1097.  !   15309. !   16258. !   30236.1   211.7  !  34.7     .7  90.9!
!  18.4! 5.48  101.0   3393.  !  8.33  153.7    1071. !   1059.  !   15309. !   16262. !   29680.7   207.8  !  33.4     .6  91.6!
!  18.8! 5.48  103.0   3397.  !  8.33  156.7    1050. !   1038.  !   15309. !   16265. !   29117.3   203.8  !  32.2     .6  92.2!
!  19.2! 5.48  104.9   3404.  !  8.33  159.7    1034. !   1022.  !   15309. !   16273. !   27998.5   196.0  !  31.0     .6  92.9!
!  19.5! 5.48  106.9   3408.  !  8.33  162.6    1013. !   1001.  !   15309. !   16277. !   27435.1   192.0  !  29.9     .6  93.5!
!  19.9! 5.48  108.8   3412.  !  8.33  165.6     993. !    981.  !   15309. !   16281. !   26879.7   188.2  !  28.8     .6  94.0!
!  20.2! 5.48  110.7   3419.  !  8.33  168.5     975. !    963.  !   15309. !   16288. !   25752.9   180.3  !  27.8     .6  94.6!
!  20.6! 5.48  112.7   3423.  !  8.33  171.5     946. !    934.  !   15309. !   16292. !   25197.5   176.4  !  26.9     .6  95.0!
!  20.9! 5.48  114.6   3427.  !  8.33  174.4     928. !    916.  !   15309. !   16296. !   24634.1   172.4  !  26.0     .6  95.4!
!  21.3! 5.48  116.6   3434.  !  8.33  177.4     914. !    901.  !   15309. !   16303. !   23515.3   164.6  !  25.2     .6  95.8!
!  21.6! 5.48  118.5   3438.  !  8.33  180.3     896. !    884.  !   15309. !   16307. !   22951.9   160.7  !  24.4     .6  96.2!
!  22.0! 5.48  120.5   3442.  !  8.33  183.3     883. !    870.  !   15309. !   16311. !   22396.4   156.8  !  23.6     .6  96.6!
!  22.4! 5.48  122.4   3449.  !  8.33  186.3     877. !    865.  !   15309. !   16319. !   21277.6   148.9  !  22.9     .6  96.9!
!  22.7! 5.48  124.3   3453.  !  8.33  189.2     865. !    853.  !   15309. !   16322. !   20714.2   145.0  !  22.1     .6  97.2!
!  23.1! 5.48  126.3   3457.  !  8.33  192.2     853. !    840.  !   15309. !   16326. !   20150.8   141.1  !  21.4     .6  97.5!
!  23.4! 5.48  128.2   3464.  !  8.33  195.1     843. !    831.  !   15309. !   16334. !   19031.9   133.2  !  20.8     .5  97.8!
!  23.8! 5.48  130.2   3468.  !  8.33  198.1     833. !    821.  !   15309. !   16338. !   18476.4   129.3  !  20.2     .5  98.0!
!  24.1! 5.48  132.1   3472.  !  8.33  201.0     824. !    812.  !   15309. !   16341. !   17913.0   125.4  !  19.6     .5  98.2!
!  24.5! 5.48  134.1   3479.  !  8.33  204.0     822. !    810.  !   15309. !   16349. !   16794.1   117.6  !  19.0     .5  98.4!
!  24.8! 5.48  136.0   3483.  !  8.33  207.0     813. !    801.  !   15309. !   16353. !   16230.7   113.6  !  18.4     .5  98.6!
!  25.2! 5.48  137.9   3487.  !  8.33  209.9     801. !    789.  !   15309. !   16357. !   15675.2   109.7  !  17.9     .5  98.8!
!  25.5! 5.48  139.9   3494.  !  8.33  212.9     789. !    777.  !   15309. !   16364. !   14548.3   101.8  !  17.4     .5  98.9!
!  25.9! 5.48  141.8   3498.  !  8.33  215.8     775. !    763.  !   15309. !   16368. !   13992.9    97.9  !  16.9     .5  99.1!
!  26.3! 5.48  143.8   3502.  !  8.33  218.8     768. !    756.  !   15309. !   16372. !   13429.4    94.0  !  16.4     .5  99.2!
!  26.6! 5.48  145.7   3509.  !  8.33  221.7     768. !    756.  !   15309. !   16379. !   12310.5    86.2  !  15.9     .5  99.3!
!  27.0! 5.48  147.7   3517.  !  8.33  224.7     767. !    755.  !   15309. !   16387. !   11191.6    78.3  !  15.3     .4  99.4!
!  27.3! 5.48  149.6   3524.  !  8.33  227.7     762. !    750.  !   15309. !   16394. !   10072.6    70.5  !  14.8     .4  99.5!
!  27.7! 5.48  151.5   3532.  !  8.33  230.6     755. !    743.  !   15309. !   16402. !    8945.7    62.6  !  14.3     .4  99.6!
!  28.0! 5.48  153.5   3539.  !  8.33  233.6     752. !    740.  !   15309. !   16410. !    7826.7    54.8  !  13.7     .4  99.7!
!  28.4! 5.48  155.4   3547.  !  8.33  236.5     741. !    729.  !   15309. !   16417. !    6707.8    47.0  !  13.2     .4  99.7!
!  28.7! 5.48  157.4   3554.  !  8.33  239.5     737. !    725.  !   15309. !   16425. !    5588.8    39.1  !  12.5     .4  99.8!
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 !  29.4!  5.48   161.3   3565.  !  8.33   245.4   741. !   729.  !   15309. !  16436. !    3977.7      27.8  !  11.2      .3  99.9!
 !  29.8!  5.48   163.2   3577.  !  8.33   248.4   738. !   726.  !   15309. !  16448. !    2223.8      15.6  !  10.5      .3  99.9!
 !  30.2!  5.48   165.1   3590.  !  8.33   251.3   731. !   719.  !   15309. !  16461. !     263.5       1.8  !   9.5      .3 100.0!
 !  30.5!  5.48   167.1   3651.  !  8.33   254.3   710. !   698.  !   15309. !  16523. !        .0        .0  !   8.3      .3 100.0!
 !  30.9!  5.48   169.0   3672.  !  8.33   257.2   716. !   704.  !   15309. !  16544. !        .0        .0  !   7.6      .2 100.0!
 !  31.2!  5.48   171.0   3693.  !  8.33   260.2   706. !   694.  !   15309. !  16566. !        .0        .0  !   6.9      .2 100.0!
 !  31.6!  5.48   172.9   3713.  !  8.33   263.1   706. !   694.  !   15309. !  16586. !        .0        .0  !   6.4      .2 100.0!
 !  31.9!  5.48   174.9   3732.  !  8.33   266.1   704. !   692.  !   15309. !  16604. !        .0        .0  !   5.8      .2 100.0!
 !  32.3!  5.48   176.8   3749.  !  8.33   269.0   704. !   691.  !   15309. !  16622. !        .0        .0  !   5.3      .2 100.0!
 !  32.6!  5.48   178.7   3764.  !  8.33   272.0   703. !   690.  !   15309. !  16638. !        .0        .0  !   4.9      .2 100.0!
 !  33.0!  5.48   180.7   3779.  !  8.33   275.0   702. !   690.  !   15309. !  16652. !        .0        .0  !   4.5      .1 100.0!
 !  33.3!  5.48   182.6   3792.  !  8.33   277.9   701. !   689.  !   15309. !  16666. !        .0        .0  !   4.1      .1 100.0!
 !  33.7!  5.48   184.6   3805.  !  8.33   280.9   700. !   688.  !   15309. !  16679. !        .0        .0  !   3.8      .1 100.0!
 !  34.1!  5.48   186.5   3817.  !  8.33   283.8   699. !   687.  !   15309. !  16691. !        .0        .0  !   3.5      .1 100.0!
 !  34.4!  5.48   188.5   3828.  !  8.33   286.8   698. !   686.  !   15309. !  16702. !        .0        .0  !   3.2      .1 100.0!
 !  34.8!  5.48   190.4   3838.  !  8.33   289.7   698. !   686.  !   15309. !  16712. !        .0        .0  !   2.9      .1 100.0!
 !  35.1!  5.48   192.3   3846.  !  8.33   292.7   698. !   686.  !   15309. !  16721. !        .0        .0  !   2.7      .1 100.0!
 !  35.5!  5.48   194.3   3853.  !  8.33   295.7   697. !   685.  !   15309. !  16728. !        .0        .0  !   2.4      .1 100.0!
 !  35.8!  5.48   196.2   3859.  !  8.33   298.6   696. !   684.  !   15309. !  16734. !        .0        .0  !   2.2      .1 100.0!
 !  36.2!  5.48   198.2   3865.  !  8.33   301.6   695. !   683.  !   15309. !  16740. !        .0        .0  !   2.1      .1 100.0!
 !  36.5!  5.48   200.1   3871.  !  8.33   304.5   694. !   682.  !   15309. !  16745. !        .0        .0  !   1.9      .1 100.0!
 !  36.9!  5.48   202.1   3875.  !  8.33   307.5   694. !   681.  !   15309. !  16750. !        .0        .0  !   1.7      .1 100.0!
 !  37.3!  5.48   204.0   3880.  !  8.33   310.4   693. !   680.  !   15309. !  16755. !        .0        .0  !   1.6      .0 100.0!
 !  37.6!  5.48   205.9   3884.  !  8.33   313.4   692. !   680.  !   15309. !  16759. !        .0        .0  !   1.4      .0 100.0!
 !  38.0!  5.48   207.9   3888.  !  8.33   316.4   691. !   679.  !   15309. !  16763. !        .0        .0  !   1.3      .0 100.0!
 !  38.3!  5.48   209.8   3891.  !  8.33   319.3   690. !   678.  !   15309. !  16766. !        .0        .0  !   1.2      .0 100.0!
 !  38.7!  5.48   211.8   3894.  !  8.33   322.3   689. !   677.  !   15309. !  16769. !        .0        .0  !   1.1      .0 100.0!
 !  39.0!  5.48   213.7   3897.  !  8.33   325.2   688. !   676.  !   15309. !  16772. !        .0        .0  !   1.0      .0 100.0!
 !  39.4!  5.48   215.7   3900.  !  8.33   328.2   687. !   675.  !   15309. !  16775. !        .0        .0  !    .9      .0 100.0!
 !  39.7!  5.48   217.6   3902.  !  8.33   331.1   686. !   674.  !   15309. !  16777. !        .0        .0  !    .9      .0 100.0!
 !  40.1!  5.48   219.5   3904.  !  8.33   334.1   685. !   673.  !   15309. !  16780. !        .0        .0  !    .8      .0 100.0!
 !  40.4!  5.48   221.5   3907.  !  8.33   337.0   684. !   672.  !   15309. !  16782. !        .0        .0  !    .7      .0 100.0!
 !  40.8!  5.48   223.4   3908.  !  8.33   340.0   684. !   671.  !   15309. !  16784. !        .0        .0  !    .7      .0 100.0!
 !  41.2!  5.48   225.4   3910.  !  8.33   343.0   683. !   670.  !   15309. !  16785. !        .0        .0  !    .6      .0 100.0!
 !  41.5!  5.48   227.3   3912.  !  8.33   345.9   682. !   670.  !   15309. !  16787. !        .0        .0  !    .6      .0 100.0!
 !  41.9!  5.48   229.3   3913.  !  8.33   348.9   681. !   669.  !   15309. !  16788. !        .0        .0  !    .5      .0 100.0!
 !  42.2!  5.48   231.2   3914.  !  8.33   351.8   680. !   668.  !   15309. !  16790. !        .0        .0  !    .5      .0 100.0!
 !  42.6!  5.48   233.1   3916.  !  8.33   354.8   679. !   667.  !   15309. !  16791. !        .0        .0  !    .4      .0 100.0!
 !  42.9!  5.48   235.1   3917.  !  8.33   357.7   678. !   666.  !   15309. !  16792. !        .0        .0  !    .4      .0 100.0!
 !  43.3!  5.48   237.0   3918.  !  8.33   360.7   677. !   665.  !   15309. !  16793. !        .0        .0  !    .4      .0 100.0!
 !  43.6!  5.48   239.0   3919.  !  8.33   363.7   676. !   664.  !   15309. !  16794. !        .0        .0  !    .3      .0 100.0!
 !  44.0!  5.48   240.9   3920.  !  8.33   366.6   675. !   663.  !   15309. !  16795. !        .0        .0  !    .3      .0 100.0!
 !  44.3!  5.48   242.9   3920.  !  8.33   369.6   674. !   662.  !   15309. !  16796. !        .0        .0  !    .3      .0 100.0!
 !  44.7!  5.48   244.8   3921.  !  8.33   372.5   673. !   661.  !   15309. !  16796. !        .0        .0  !    .3      .0 100.0!
 !  45.1!  5.48   246.7   3922.  !  8.33   375.5   673. !   660.  !   15309. !  16797. !        .0        .0  !    .2      .0 100.0!
 !  45.4!  5.48   248.7   3700.  !  8.33   378.4   672. !   659.  !   15309. !  16798. !        .0        .0  !    .2      .0 100.0!
 !  45.8!  5.48   250.6   3709.  !  8.33   381.4   671. !   659.  !   15309. !  16798. !        .0        .0  !    .2      .0 100.0!
 !  46.1!  5.48   252.6   3717.  !  8.33   384.4   670. !   658.  !   15309. !  16799. !        .0        .0  !    .2      .0 100.0!
 !  46.5!  5.48   254.5   3718.  !  8.33   387.3   669. !   657.  !   15309. !  16799. !        .0        .0  !    .2      .0 100.0!
 !  46.8!  5.48   256.5   3718.  !  8.33   390.3   668. !   656.  !   15309. !  16800. !        .0        .0  !    .2      .0 100.0!
 !  47.2!  5.48   258.4   3718.  !  8.33   393.2   667. !   655.  !   15309. !  16800. !        .0        .0  !    .1      .0 100.0!
 !  47.5!  5.48   260.3   3719.  !  8.33   396.2   666. !   654.  !   15309. !  16800. !        .0        .0  !    .1      .0 100.0!
 !  47.9!  5.48   262.3   3719.  !  8.33   399.1   665. !   653.  !   15309. !  16801. !        .0        .0  !    .1      .0 100.0!
 !  48.3!  5.48   264.2   3719.  !  8.33   402.1   664. !   652.  !   15309. !  16801. !        .0        .0  !    .1      .0 100.0!
 !  48.6!  5.48   266.2   3720.  !  8.33   405.0   663. !   651.  !   15309. !  16801. !        .0        .0  !    .1      .0 100.0!
 !  49.0!  5.48   268.1   3720.  !  8.33   408.0   663. !   650.  !   15309. !  16802. !        .0        .0  !    .1      .0 100.0!
 !  49.3!  5.48   270.1   3720.  !  8.33   411.0   662. !   649.  !   15309. !  16802. !        .0        .0  !    .1      .0 100.0!
 !  49.7!  5.48   272.0   3720.  !  8.33   413.9   661. !   649.  !   15309. !  16802. !        .0        .0  !    .1      .0 100.0!
 !  50.0!  5.48   273.9   3720.  !  8.33   416.9   660. !   648.  !   15309. !  16802. !        .0        .0  !    .1      .0 100.0!
 !  50.4!  5.48   275.9   3721.  !  8.33   419.8   659. !   647.  !   15309. !  16802. !        .0        .0  !    .1      .0 100.0!
 !  50.7!  5.48   277.8   3721.  !  8.33   422.8   658. !   646.  !   15309. !  16802. !        .0        .0  !    .1      .0 100.0!
 !  51.1!  5.48   279.8   3721.  !  8.33   425.7   657. !   645.  !   15309. !  16803. !        .0        .0  !    .1      .0 100.0!
 !  51.4!  5.48   281.7   3721.  !  8.33   428.7   656. !   644.  !   15309. !  16803. !        .0        .0  !    .0      .0 100.0!
 !  51.8!  5.48   283.7   3721.  !  8.33   431.7   655. !   643.  !   15309. !  16803. !        .0        .0  !    .0      .0 100.0!
 !  52.2!  5.48   285.6   3721.  !  8.33   434.6   654. !   642.  !   15309. !  16803. !        .0        .0  !    .0      .0 100.0!
 !  52.5!  5.48   287.5   3721.  !  8.33   437.6   653. !   641.  !   15309. !  16803. !        .0        .0  !    .0      .0 100.0!
 !  52.9!  5.48   289.5   3722.  !  8.33   440.5   653. !   640.  !   15309. !  16803. !        .0        .0  !    .0      .0 100.0!
 !  53.2!  5.48   291.4   3722.  !  8.33   443.5   652. !   639.  !   15309. !  16803. !        .0        .0  !    .0      .0 100.0!
 !  53.6!  5.48   293.4   3722.  !  8.33   446.4   651. !   639.  !   15309. !  16803. !        .0        .0  !    .0      .0 100.0!
 !  53.9!  5.48   295.3   3722.  !  8.33   449.4   650. !   638.  !   15309. !  16803. !        .0        .0  !    .0      .0 100.0!
 !  54.3!  5.48   297.3   3722.  !  8.33   452.4   649. !   637.  !   15309. !  16804. !        .0        .0  !    .0      .0 100.0!
 !  54.6!  5.48   299.2   3722.  !  8.33   455.3   648. !   636.  !   15309. !  16804. !        .0        .0  !    .0      .0 100.0!
 !  55.0!  5.48   301.1   3722.  !  8.33   458.3   647. !   635.  !   15309. !  16804. !        .0        .0  !    .0      .0 100.0!
 !  55.3!  5.48   303.1   3722.  !  8.33   461.2   646. !   634.  !   15309. !  16804. !        .0        .0  !    .0      .0 100.0!
 !  55.7!  5.48   305.0   3722.  !  8.33   464.2   645. !   633.  !   15309. !  16804. !        .0        .0  !    .0      .0 100.0!
 !  56.1!  5.48   307.0   3722.  !  8.33   467.1   644. !   632.  !   15309. !  16804. !        .0        .0  !    .0      .0 100.0!
 !  56.4!  5.48   308.9   3722.  !  8.33   470.1   643. !   631.  !   15309. !  16804. !        .0        .0  !    .0      .0 100.0!
 !  56.8!  5.48   310.9   3722.  !  8.33   473.0   643. !   630.  !   15309. !  16804. !        .0        .0  !    .0      .0 100.0!
 !  57.1!  5.48   312.8   3722.  !  8.33   476.0   642. !   629.  !   15309. !  16804. !        .0        .0  !    .0      .0 100.0!
 !  57.5!  5.48   314.7   3722.  !  8.33   479.0   641. !   629.  !   15309. !  16804. !        .0        .0  !    .0      .0 100.0!
 !  57.8!  5.48   316.7   3722.  !  8.33   481.9   640. !   628.  !   15309. !  16804. !        .0        .0  !    .0      .0 100.0!
 !  58.2!  5.48   318.6   3722.  !  8.33   484.9   639. !   627.  !   15309. !  16804. !        .0        .0  !    .0      .0 100.0!
 !  58.5!  5.48   320.6   3722.  !  8.33   487.8   638. !   626.  !   15309. !  16804. !        .0        .0  !    .0      .0 100.0!
 !  58.9!  5.48   322.5   3722.  !  8.33   490.8   637. !   625.  !   15309. !  16804. !        .0        .0  !    .0      .0 100.0!
 !  59.2!  5.48   324.5   3722.  !  8.33   493.7   636. !   624.  !   15309. !  16804. !        .0        .0  !    .0      .0 100.0!
 !  59.6!  5.48   326.4   3722.  !  8.33   496.7   635. !   623.  !   15309. !  16804. !        .0        .0  !    .0      .0 100.0!
 !  60.0!  5.48   328.3   3722.  !  8.33   499.7   634. !   622.  !   15309. !  16804. !        .0        .0  !    .0      .0 100.0!
 !  60.3!  2.38   329.2    941.  !  8.33   502.6   627. !   615.  !   15303. !  16772. !        .0        .0  !    .0      .0 100.0!
 !  60.7!  2.38   330.0    941.  !  8.33   505.6   627. !   614.  !   15303. !  16772. !        .0        .0  !    .0      .0 100.0!
 !  61.0!  2.38   330.9    941.  !  8.33   508.5   626. !   613.  !   15303. !  16772. !        .0        .0  !    .0      .0 100.0!
 !  61.4!  2.38   331.7    941.  !  8.33   511.5   625. !   613.  !   15303. !  16772. !        .0        .0  !    .0      .0 100.0!
 !  61.7!  2.38   332.6    941.  !  8.33   514.4   624. !   612.  !   15303. !  16772. !        .0        .0  !    .0      .0 100.0!
 !  62.1!  2.38   333.4    941.  !  8.33   517.4   623. !   611.  !   15303. !  16772. !        .0        .0  !    .0      .0 100.0!
 !  62.4!  2.38   334.3    941.  !  8.33   520.4   622. !   610.  !   15303. !  16772. !        .0        .0  !    .0      .0 100.0!
 !  62.8!  2.38   335.1    941.  !  8.33   523.3   621. !   609.  !   15303. !  16772. !        .0        .0  !    .0      .0 100.0!
 !  63.2!  2.38   335.9    941.  !  8.33   526.3   620. !   608.  !   15303. !  16772. !        .0        .0  !    .0      .0 100.0!
 !  63.5!  2.38   336.8    941.  !  8.33   529.2   619. !   607.  !   15303. !  16772. !        .0        .0  !    .0      .0 100.0!
 !  63.9!  2.38   337.6    941.  !  8.33   532.2   618. !   606.  !   15303. !  16772. !        .0        .0  !    .0      .0 100.0!
 !  64.2!  2.38   338.5    941.  !  8.33   535.1   617. !   605.  !   15303. !  16772. !        .0        .0  !    .0      .0 100.0!
 !  64.6!  2.38   339.3    941.  !  8.33   538.1   616. !   604.  !   15303. !  16772. !        .0        .0  !    .0      .0 100.0!
 !  64.9!  2.38   340.2    941.  !  8.33   541.0   615. !   603.  !   15303. !  16772. !        .0        .0  !    .0      .0 100.0!
 !  65.3!  2.38   341.0    941.  !  8.33   544.0   614. !   602.  !   15303. !  16772. !        .0        .0  !    .0      .0 100.0!
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 !  65.6!  2.38   341.9    941.  !  8.33   547.0    613. !    601.  !   15303. !   16772. !        .0       .0  !    .0      .0 100.0!
 !  66.0!  2.38   342.7    941.  !  8.33   549.9    612. !    599.  !   15303. !   16772. !        .0       .0  !    .0      .0 100.0!
 !  66.3!  2.38   343.6    941.  !  8.33   552.9    610. !    598.  !   15303. !   16772. !        .0       .0  !    .0      .0 100.0!
 !  66.7!  2.38   344.4    941.  !  8.33   555.8    609. !    597.  !   15303. !   16772. !        .0       .0  !    .0      .0 100.0!
 !  67.1!  2.38   345.2    941.  !  8.33   558.8    608. !    596.  !   15303. !   16772. !        .0       .0  !    .0      .0 100.0!
 !  67.4!  2.38   346.1    941.  !  8.33   561.7    607. !    595.  !   15303. !   16772. !        .0       .0  !    .0      .0 100.0!
 !  67.8!  2.38   346.9    941.  !  8.33   564.7    606. !    594.  !   15303. !   16772. !        .0       .0  !    .0      .0 100.0!
 !  68.1!  2.38   347.8    941.  !  8.33   567.7    605. !    593.  !   15303. !   16772. !        .0       .0  !    .0      .0 100.0!
 !  68.5!  2.38   348.6    941.  !  8.33   570.6    604. !    592.  !   15303. !   16772. !        .0       .0  !    .0      .0 100.0!
 !  68.8!  2.38   349.5    941.  !  8.33   573.6    603. !    591.  !   15303. !   16772. !        .0       .0  !    .0      .0 100.0!
 !  69.2!  2.38   350.3    941.  !  8.33   576.5    602. !    590.  !   15303. !   16772. !        .0       .0  !    .0      .0 100.0!
 !  69.5!  2.38   351.2    941.  !  8.33   579.5    601. !    589.  !   15303. !   16772. !        .0       .0  !    .0      .0 100.0!
 !  69.9!  2.38   352.0    941.  !  8.33   582.4    601. !    589.  !   15303. !   16772. !        .0       .0  !    .0      .0 100.0!
 !  70.2!  2.38   352.8    941.  !  8.33   585.4    600. !    588.  !   15303. !   16772. !        .0       .0  !    .0      .0 100.0!
 !  70.6!  2.38   353.7    941.  !  8.33   588.4    600. !    588.  !   15303. !   16772. !        .0       .0  !    .0      .0 100.0!
 !  71.0!  2.38   354.5    941.  !  8.33   591.3    599. !    587.  !   15303. !   16772. !        .0       .0  !    .0      .0 100.0!
 !  71.3!  2.38   355.4    941.  !  8.33   594.3    599. !    587.  !   15303. !   16772. !        .0       .0  !    .0      .0 100.0!
 !  71.7!  2.38   356.2    941.  !  8.33   597.2    598. !    586.  !   15303. !   16772. !        .0       .0  !    .0      .0 100.0!
 !  72.0!  2.38   357.1    941.  !  8.33   600.2    598. !    586.  !   15303. !   16772. !        .0       .0  !    .0      .0 100.0!
 !  72.4!  2.38   357.9    941.  !  8.33   603.1    597. !    585.  !   15303. !   16772. !        .0       .0  !    .0      .0 100.0!
 !  72.7!  2.38   358.8    941.  !  8.33   606.1    597. !    585.  !   15303. !   16772. !        .0       .0  !    .0      .0 100.0!
 !  73.1!  2.38   359.6    941.  !  8.33   609.0    596. !    584.  !   15303. !   16772. !        .0       .0  !    .0      .0 100.0!
 !  73.4!  2.38   360.4    941.  !  8.33   612.0    595. !    583.  !   15303. !   16772. !        .0       .0  !    .0      .0 100.0!
 !  73.8!  2.38   361.3    941.  !  8.33   615.0    594. !    582.  !   15303. !   16772. !        .0       .0  !    .0      .0 100.0!
 !  74.2!  2.38   362.1    941.  !  8.33   617.9    593. !    581.  !   15303. !   16772. !        .0       .0  !    .0      .0 100.0!
 !  74.5!  2.38   363.0    941.  !  8.33   620.9    592. !    580.  !   15303. !   16772. !        .0       .0  !    .0      .0 100.0!
 !  74.9!  2.38   363.8    941.  !  8.33   623.8    592. !    579.  !   15303. !   16772. !        .0       .0  !    .0      .0 100.0!
 !  75.2!  2.38   364.7    941.  !  8.33   626.8    591. !    579.  !   15303. !   16772. !        .0       .0  !    .0      .0 100.0!
 !  75.6!  2.38   365.5    941.  !  8.33   629.7    590. !    578.  !   15303. !   16772. !        .0       .0  !    .0      .0 100.0!
 !  75.9!  2.38   366.4    941.  !  8.33   632.7    589. !    577.  !   15303. !   16772. !        .0       .0  !    .0      .0 100.0!
 !  76.3!  2.38   367.2    941.  !  8.33   635.7    588. !    576.  !   15303. !   16772. !        .0       .0  !    .0      .0 100.0!
 !  76.6!  2.38   368.0    941.  !  8.33   638.6    587. !    574.  !   15303. !   16772. !        .0       .0  !    .0      .0 100.0!
 !  77.0!  2.38   368.9    941.  !  8.33   641.6    586. !    573.  !   15303. !   16772. !        .0       .0  !    .0      .0 100.0!
 !  77.3!  2.38   369.7    941.  !  8.33   644.5    585. !    572.  !   15303. !   16772. !        .0       .0  !    .0      .0 100.0!
 !  77.7!  2.38   370.6    941.  !  8.33   647.5    584. !    571.  !   15303. !   16772. !        .0       .0  !    .0      .0 100.0!
 !  78.1!  2.38   371.4    941.  !  8.33   650.4    583. !    570.  !   15303. !   16772. !        .0       .0  !    .0      .0 100.0!
 !  78.4!  2.38   372.3    941.  !  8.33   653.4    582. !    569.  !   15303. !   16772. !        .0       .0  !    .0      .0 100.0!
 !  78.8!  2.38   373.1    941.  !  8.33   656.4    581. !    569.  !   15303. !   16772. !        .0       .0  !    .0      .0 100.0!
 !  79.1!  2.38   374.0    941.  !  8.33   659.3    580. !    568.  !   15303. !   16772. !        .0       .0  !    .0      .0 100.0!
 !  79.5!  2.38   374.8    941.  !  8.33   662.3    579. !    567.  !   15303. !   16772. !        .0       .0  !    .0      .0 100.0!
 !  79.8!  2.38   375.7    941.  !  8.33   665.2    578. !    566.  !   15303. !   16772. !        .0       .0  !    .0      .0 100.0!
 !  80.2!   .00   375.7     67.  !   .00   665.2    149. !    149.  !   15282. !   16724. !        .0       .0  !    .0      .0 100.0!
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SNAP_A02. TXT

ANNULAR SNAPSHOT

Bullhead Well Control Simulation Snapshot
Pump Flow Rate,gal/m = 350.
Simulation Time,min= 1.

MD ft	TVD ft	Dev Deg	Pres psia	Temp oF	Vavg ft/s	fm (frac)	fg (frac)	fw (frac)	2P Den lb/gal	Gh psi/ft	Gf psi/ft	Gacc psi/ft	Ce sips	SCF G scf	Bbl W bbl	Swell bbl
0.	0.	90.00	3471.	130.	.000	1.000	.000	.000	18.33	.949	.234	.000	.16E-05	.0	.0	.000
500.	500.	.73	3934.	134.	2.995	1.000	.000	.000	18.33	.951	.026	.000	.16E-05	.0	.0	.000
1000.	1000.	.73	4395.	137.	2.994	1.000	.000	.000	18.26	.948	.024	.000	.16E-05	.0	.0	.000
1500.	1500.	.73	4858.	141.	2.994	1.000	.000	.000	18.27	.948	.024	.000	.16E-05	.0	.0	.000
2000.	2000.	.73	5320.	144.	2.993	1.000	.000	.000	18.27	.948	.023	.000	.16E-05	.0	.0	.000
2500.	2500.	.73	5783.	148.	2.993	1.000	.000	.000	18.27	.948	.022	.000	.16E-05	.0	.0	.000
3000.	3000.	.73	6246.	151.	2.993	1.000	.000	.000	18.27	.948	.022	.000	.16E-05	.0	.0	.000
3500.	3500.	.73	6709.	155.	2.992	1.000	.000	.000	18.27	.948	.022	.000	.15E-05	.0	.0	.000
4000.	4000.	.73	7172.	158.	2.992	1.000	.000	.000	18.28	.949	.022	.000	.15E-05	.0	.0	.000
4500.	4500.	.73	7636.	162.	2.992	1.000	.000	.000	18.28	.949	.022	.000	.15E-05	.0	.0	.000
5000.	5000.	.73	8099.	166.	2.991	1.000	.000	.000	18.28	.949	.022	.000	.15E-05	.0	.0	.000
5500.	5500.	.73	8563.	169.	2.991	1.000	.000	.000	18.28	.949	.021	.000	.15E-05	.0	.0	.000
6000.	6000.	.73	9027.	173.	2.991	1.000	.000	.000	18.28	.949	.021	.000	.15E-05	.0	.0	.000
6500.	6499.	.73	9491.	176.	2.991	1.000	.000	.000	18.28	.949	.021	.000	.15E-05	.0	.0	.000
7000.	6999.	.73	9955.	180.	2.991	1.000	.000	.000	18.29	.949	.021	.000	.14E-05	.0	.0	.000
7500.	7499.	.73	10419.	183.	2.990	1.000	.000	.000	18.29	.949	.021	.000	.14E-05	.0	.0	.000
8000.	7999.	.73	10883.	187.	2.990	1.000	.000	.000	18.29	.949	.021	.000	.14E-05	.0	.0	.000
8500.	8499.	.73	11347.	190.	2.990	1.000	.000	.000	18.29	.949	.021	.000	.14E-05	.0	.0	.000
9000.	8999.	.73	11812.	194.	2.990	1.000	.000	.000	18.29	.949	.020	.000	.14E-05	.0	.0	.000
9500.	9499.	.73	12276.	197.	2.990	1.000	.000	.000	18.29	.949	.020	.000	.14E-05	.0	.0	.000
10000.	9999.	.73	12740.	201.	2.990	1.000	.000	.000	18.29	.949	.020	.000	.14E-05	.0	.0	.000
10500.	10499.	.73	13205.	205.	2.990	1.000	.000	.000	18.29	.949	.020	.000	.14E-05	.0	.0	.000
11000.	10999.	.73	13669.	208.	2.991	1.000	.000	.000	18.29	.949	.020	.000	.14E-05	.0	.0	.000
11500.	11499.	.73	14134.	212.	2.991	1.000	.000	.000	18.28	.949	.020	.000	.14E-05	.0	.0	.000
12150.	12149.	.72	14718.	216.	3.090	.997	.003	.000	17.70	.919	.020	.000	.13E-05	1354.7	.0	.957
12650.	12649.	1.82	14862.	220.	2.442	.195	.805	.000	5.69	.295	.006	.000	.15E-04	54547.5	.0	.183
12900.	12899.	2.47	14904.	222.	2.443	.037	.963	.000	3.31	.172	.004	.000	.17E-04	32507.6	.0	.017
13400.	13398.	2.46	14975.	225.	4.447	.007	.993	.000	2.86	.148	.006	.000	.17E-04	36669.7	.0	.004
14000.	13998.	2.46	15060.	229.	4.452	.001	.999	.000	2.75	.143	.002	.000	.17E-04	44042.9	.0	.000
14500.	14497.	2.47	15129.	233.	4.429	.000	1.000	.000	2.73	.142	.002	.000	.17E-04	36757.2	.0	.000
15000.	14997.	2.46	15199.	237.	4.433	.000	1.000	.000	2.72	.141	.002	.000	.17E-04	36585.7	.0	.000
15600.	15596.	2.46	15281.	241.	4.438	.001	.999	.000	2.71	.141	.003	.000	.16E-04	43653.0	.0	.000
15800.	15796.	2.47	15309.	242.	4.960	.001	.999	.000	2.70	.140	.004	.000	.16E-04	12999.5	.0	.000
15900.	15896.	2.46	15338.	243.	20.334	.036	.949	.015	3.32	.172	.122	.000	.15E-04	6171.3	.0	.002
16000.	15996.	2.47	15368.	244.	20.347	.036	.949	.015	3.32	.172	.122	.000	.15E-04	6167.0	.0	.002
16100.	16096.	2.47	15397.	244.	20.360	.036	.949	.015	3.32	.172	.122	.000	.15E-04	6162.6	.0	.002
16200.	16195.	2.47	15426.	245.	20.373	.036	.949	.015	3.32	.172	.122	.000	.15E-04	6158.2	.0	.002
16300.	16295.	2.46	15456.	246.	20.386	.036	.949	.015	3.31	.172	.122	.000	.15E-04	6153.8	.0	.002
16400.	16395.	2.47	15485.	246.	20.399	.036	.949	.015	3.31	.172	.122	.000	.15E-04	6149.4	.0	.002
16500.	16495.	5.13	15514.	247.	20.412	.036	.949	.015	3.31	.172	.122	.000	.15E-04	6144.9	.0	.002
16600.	16595.	4.45	15544.	248.	20.426	.036	.949	.015	3.31	.172	.122	.000	.15E-04	6140.4	.0	.002
16700.	16695.	2.56	15573.	249.	20.440	.036	.949	.015	3.30	.171	.122	.000	.15E-04	6135.9	.0	.002
16800.	16794.	2.56	15602.	249.	20.453	.035	.949	.015	3.30	.171	.122	.000	.15E-04	6131.3	.0	.002
16900.	16894.	.00	15632.	250.	20.467	.035	.949	.015	3.30	.171	.122	.000	.15E-04	6126.7	.0	.002
17000.	16994.	3.63	15661.	251.	20.481	.035	.949	.015	3.30	.171	.122	.000	.15E-04	6122.1	.0	.002
17100.	17094.	3.62	15690.	251.	20.495	.035	.949	.015	3.29	.171	.122	.000	.14E-04	6117.4	.0	.002
17300.	17293.	5.73	15822.	253.	31.245	.035	.949	.015	3.29	.171	.486	.000	.14E-04	8025.1	.1	.003
														387024.2		

SNAP_P02. TXT

DRILLSTRING SNAPSHOT

Bullhead Well Control Simulation Snapshot
Pump Flow Rate,gal/m = 230.
Simulation Time,min= 1.

MD	TVD	Dev	Pres	Temp	Vavg	PV	YP	MW	Gh	Gf	Gacc	Ceff	fMUD1	fMUD2
ft	ft	Deg	psia	oF	ft/s	cp	lb/100sf	lb/gal	psi/ft	psi/ft	psi/ft	sips		
0.	0.	90.00	2954.	125.00	7.6	39.6	13.4	18.49	.942	.075	.000	.17E-05	.000	1.000
500.	500.	.73	3411.	128.69	5.1	39.6	13.4	18.49	.942	.030	.000	.17E-05	.425	.575
1000.	1000.	.73	3867.	132.39	5.1	35.3	11.8	18.26	.942	.030	.000	.17E-05	1.000	.000
1500.	1500.	.73	4323.	136.08	5.1	34.2	11.4	18.26	.942	.030	.000	.16E-05	1.000	.000
2000.	2000.	.73	4780.	139.78	5.1	33.3	11.1	18.27	.942	.030	.000	.16E-05	1.000	.000
2500.	2500.	.73	5236.	143.47	5.1	32.3	10.8	18.27	.942	.030	.000	.16E-05	1.000	.000
3000.	3000.	.73	5692.	147.17	5.1	31.4	10.5	18.27	.942	.030	.000	.16E-05	1.000	.000
3500.	3500.	.73	6149.	150.86	5.1	30.6	10.2	18.27	.942	.030	.000	.16E-05	1.000	.000
4000.	4000.	.73	6605.	154.56	5.1	29.8	9.9	18.27	.942	.030	.000	.15E-05	1.000	.000
4500.	4500.	.73	7061.	158.25	5.1	29.0	9.7	18.27	.942	.030	.000	.15E-05	1.000	.000
5000.	5000.	.73	7518.	161.95	5.1	28.3	9.4	18.27	.942	.030	.000	.15E-05	1.000	.000
5500.	5500.	.73	7974.	165.64	5.1	27.6	9.2	18.28	.942	.030	.000	.15E-05	1.000	.000
6000.	6000.	.73	8430.	169.33	5.1	27.0	9.0	18.28	.942	.030	.000	.15E-05	1.000	.000
6500.	6499.	.73	8887.	173.03	5.1	26.4	8.8	18.28	.942	.030	.000	.15E-05	1.000	.000
7000.	6999.	.73	9343.	176.72	5.1	25.8	8.6	18.28	.942	.030	.000	.15E-05	1.000	.000
7500.	7499.	.73	9799.	180.42	5.1	25.2	8.4	18.28	.942	.030	.000	.15E-05	1.000	.000
8000.	7999.	.73	10256.	184.11	5.1	24.7	8.2	18.28	.942	.030	.000	.14E-05	1.000	.000
8500.	8499.	.73	10712.	187.81	5.1	24.2	8.1	18.28	.942	.030	.000	.14E-05	1.000	.000
9000.	8999.	.73	11168.	191.50	5.1	23.7	7.9	18.28	.942	.030	.000	.14E-05	1.000	.000
9500.	9499.	.73	11625.	195.20	5.1	23.2	7.7	18.28	.942	.030	.000	.14E-05	1.000	.000
10000.	9999.	.73	12081.	198.89	5.1	22.8	7.6	18.28	.942	.030	.000	.14E-05	1.000	.000
10500.	10499.	.73	12537.	202.58	5.1	22.4	7.5	18.27	.942	.030	.000	.14E-05	1.000	.000
11000.	10999.	.73	12994.	206.28	5.1	22.0	7.3	18.27	.942	.030	.000	.14E-05	1.000	.000
11500.	11499.	.73	13450.	209.97	5.1	21.6	7.2	18.27	.942	.030	.000	.14E-05	1.000	.000
12150.	12149.	.72	14043.	214.78	5.1	21.1	7.0	18.27	.942	.030	.000	.14E-05	1.000	.000
12650.	12649.	1.82	14395.	218.47	12.3	20.8	6.9	18.26	.942	.239	.000	.14E-05	1.000	.000
13150.	13148.	2.46	14746.	222.17	12.3	20.4	6.8	18.25	.942	.239	.000	.14E-05	1.000	.000
13650.	13648.	2.47	15097.	225.86	12.3	20.1	6.7	18.25	.942	.239	.000	.14E-05	1.000	.000
14150.	14147.	2.46	15449.	229.55	12.3	19.8	6.6	18.24	.942	.239	.000	.14E-05	1.000	.000
14650.	14647.	2.47	15800.	233.25	12.3	19.5	6.5	18.23	.942	.239	.000	.14E-05	1.000	.000
15150.	15146.	2.46	16152.	236.94	12.3	19.2	6.4	18.22	.942	.239	.000	.14E-05	1.000	.000
15800.	15796.	2.47	16608.	241.75	12.3	18.9	6.3	18.21	.942	.239	.000	.14E-05	1.000	.000
16300.	16295.	2.46	16587.	245.44	22.1	18.6	6.2	18.19	.942	.984	.000	.14E-05	1.000	.000
16700.	16695.	3.83	16570.	248.40	22.1	18.3	6.1	18.18	.942	.984	.000	.14E-05	1.000	.000
17300.	17293.	4.05	16544.	252.83	22.1	18.0	6.0	18.16	.942	.984	.000	.15E-05	1.000	.000

Pressure Drop Across MWD Tool = 0. psi
Pressure Drop Across Mud Motor = 0. psi
Pressure Drop Across Jet Bit = 722. psi