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1. ABSTRACT

This Quarter has been divided between running experiments and the installation of the drill-pipe rotation system. In addition, valves and piping were relocated, and three viewports were installed. Detailed design work is proceeding on a system to elevate the drill-string section.

Design of the first prototype version of a Foam Generator has been finalized, and fabrication is underway. This will be used to determine the relationship between surface roughness and "slip" of foams at solid boundaries. Additional cups and rotors are being machined with different surface roughness.

Some experiments on cuttings transport with aerated fluids have been conducted at EPET. Theoretical modeling of cuttings transport with aerated fluids is proceeding.

The development of theoretical models to predict frictional pressure losses of flowing foam is in progress.

The new board design for instrumentation to measure cuttings concentration is now functioning with an acceptable noise level. The ultrasonic sensors are stable up to 190ºF. Static tests with sand in an annulus indicate that the system is able to distinguish between different sand concentrations.

Viscometer tests with foam, generated by the Dynamic Test Facility (DTF), are continuing.

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2. EXECUTIVE SUMMARY OF PROGRESS

Flow Loop Construction (**Tasks 4**)

This Quarter has been divided between running experiments and the installation of the drill-pipe rotation system. On June 9, 2003 experiments were halted and construction activities began. All five view ports (a 2-in, a 3-in., and three 6-inch) were received during this quarter. Incoming piping to the drill section was re-routed to make room for the pipe-rotation equipment. In addition, valves and piping were relocated, and the following components were installed: three view ports (2-in, 3-in and one 6-in), the donated SWACO drilling choke, and two basket strainers to remove fine solids from flow returning to the holding tanks. The remaining two 6-inch view ports will be installed later after some tests are conducted and a judgment can be made about the vulnerability of the view ports to scratching by a flowing slurry. The strainers help protect and minimize wear of four different pumps that take water from the holding tanks and circulate it through the ACTS Flow Loop.

All components for the new simulated drill string have been received and are being assembled. The pipe rotation equipment is essentially complete, and the new hydraulic power unit has been received.

Lastly, detailed design work is proceeding on a system to elevate the drill-string section. Section 3 of this report provides additional details about the ACTS Flow Loop.

Development of a Foam Generator/Viscometer for EPET Conditions (**Task 9b**).

During this quarter, design of the first prototype version of a Foam Generator has been finalized, and fabrication is underway. The remaining component parts for the Foam Viscometer (RS300 Rheometer) have been ordered, but all parts have not yet been received.

One of the objectives of this research task is to determine the relationship between surface roughness and "slip" of foams at solid boundaries. Hence, additional cups and rotors are being machined with different surface roughness in order to quantify the affects of wall roughness and how this affects measurements of viscosity. In order to achieve these objectives, four additional rheometer cups and cylindrical rotors are being made with different surface roughness. The initial tests will be conducted over a range of foam parameters that include: foam quality, bubble size, shear rates, wall roughness, and one or more surfactants. Foams for these initial tests are being generated by using the existing Dynamic Test Facility (DTF), a small-scale flow loop. Connection of the RS300 Rheometer to the DTF was completed during this quarter. Low-pressure, ambient-temperature testing of foam is now underway. When the Foam Generator becomes available, additional tests will be conducted over a broad range of pressures and temperatures. This research project is discussed further in Section 4.

Study of Cuttings Transport with Aerated Mud Under Elevated Pressure and Temperature Conditions (**Task 10**).

Experiments with aerated fluids have been conducted at EPET. In addition, experiments on cuttings transport with aerated fluids have been conducted at EPET. Theoretical modeling of cuttings transport with aerated fluids is proceeding. A two-phase (gas/liquid) flow model is under development to predict the pressure drop in the horizontal annulus under EPET. Analysis of the collected data is in progress. Additional modification of the cuttings collection system are being considered in order to obtain the desired accurate measurement of cuttings weight in the annular test section. Additional discussion of this task is provided in Section 5.

Study of Cuttings Transport with Foam under Elevated Pressure and Elevated Temperature Conditions (**Task 13**).

This research is a continuation of the two research projects on foam rheology and cuttings transport. The development of theoretical models to predict frictional pressure losses of flowing foam is in progress. In addition, an initial test matrix for cuttings-transport experiments with foam in the ACTF has been prepared. These plans are discussed further in Section 6.

Research on Instrumentation to Measure Cuttings Concentration and Distribution in a Flowing Slurry (**Task 11**)

The printed circuit board noise problem has addressed and reduced significantly. The new board design is now functioning with an acceptable noise level. In addition, temperature sensitivity tests have been conducted to determine the acceptable temperature range for the sensor operation. The ultrasonic sensors are stable up to 190^{o}F. Static tests with sand in an annulus indicate that the system is able to distinguish between different sand concentrations. Development of the data acquisition software is continuing. This software includes the use of a neural network algorithm to properly model the nonlinear nature of a flowing slurry. Additional discussion of this task in given in Section 7.

Research on Instrumentation to Measure Foam Properties while Transporting Cuttings (**Task 12**).

Section 8 discusses recent advances in capturing and imaging foam, including new digital cameras, software, and a new imaging technique. These apply to the Dynamic Testing Facility, the ACTF and the new Foam Generator/Viscometer, which is being developed. Viscometer tests with foam, generated by the Dynamic Testing Facility (DTF), are continuing.

Safety Program for the ACTS Flow Loop (**Task 1S**)
Section 9 reports on the current status of the safety program. This includes a revised status sheet and a list of training courses with brief descriptions of each.

Activities towards Technology Transfer, Developing Contacts with Petroleum & Service Company Members, and Addition of JIP Members.

The next ACTS Advisory Board Meeting will be held on November 18, 2003. A drilling manager from ConocoPhillips did visit our facilities during this past quarter. His reactions were favorable, and there is a good possibility that this company may join Tulsa University's Drilling Research Program. However, there is a very low probability that any new JIP members will join the ACTS Project during the last year (Year-5) of the project due to the cost, viz., $64,000. Section 10 provides some additional information on this topic.

SUMMARY OF CURRENT TASKS FOR ACTS PROJECT

This is the fourth quarterly progress report for Year-4 of the ACTS Project. It includes a review of progress made in: 1) Flow Loop construction and development and 2) research tasks during the period of time between April 1, 2003 and June 30, 2003.

This report presents a review of progress on the following specific tasks.

a) Design and development of an Advanced Cuttings Transport Facility
Task 4: Addition of a Pipe Rotation System.

b) New research project (**Task 9b**): "Development of a Foam Generator/Viscometer for Elevated Pressure and Elevated Temperature (EPET) Conditions".

d) Research project (**Task 10**): "Study of Cuttings Transport with Aerated Mud Under Elevated Pressure and Temperature Conditions".

e) Research on three instrumentation tasks to measure:
- Cuttings concentration and distribution in a flowing slurry (**Task 11**), and
- Foam texture while transporting cuttings. (**Task 12**),
- Viscosity of Foam under EPET (**Task 9b**).

f) New Research project (**Task 13**): "Study of Cuttings Transport with Foam under Elevated Pressure and Temperature Conditions".

g) Development of a Safety program for the ACTS Flow Loop.
Progress on a comprehensive safety review of all flow-loop components and operational procedures. (**Task 1S**).

h) Activities towards technology transfer and developing contacts with Petroleum and service company members, and increasing the number of JIP members.

Note: Flow-Loop construction Tasks 1 – 3 and Research Tasks 6, 7, 8 and 9a were **completed during the first three years of this five-year project.**

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STUDY OF CUTTINGS TRANSPORT WITH AERATED MUD UNDER ELEVATED PRESSURE AND TEMPERATURE CONDITIONS

STUDY OF CUTTINGS TRANSPORT WITH FOAM UNDER ELEVATED PRESSURE AND ELEVATED TEMPERATURE CONDITIONS

SAFETY PROGRAM (Task 1S)

3. ACTF DESIGN AND CONSTRUCTION ACCOMPLISHMENTS (Task 4)

This Quarter has been divided between running experiments and the installation of the new drill-pipe rotation system. On June 9, 2003 experiments were halted and construction activities began.

Figure 3.1 – Piping Changes to Accommodate Rotation System

Figure 3.2 – Piping to Drill Section Re-routed to Accommodate Rotation System

Figure 3.3 – Relocation of Valves and Piping

Figure 3.4 - Two-Inch View Port

Figure 3.5 – Three-Inch View Port

Figure 3.6 - The Donated SWACO Choke Valve

Figure 3.7 - Installed Strainers

Figure 3.8 – New Drill String

All components for the new drill string have been received and are being assembled.

Figure 3.9 – Components of Drive System to Rotate Pipe

The pipe rotation equipment is essentially complete.

Figure 3.10 - New Hydraulic Power Unit to Rotate Pipe

Lastly, in addition to installation of the Drill-Pipe Rotation System, work is proceeding on the detailed design of an elevation system that can vary the angle-of-inclination between horizontal and vertical. This capability will enable cuttings-transport tests at different hole-inclination angles and provide simulation of an important drilling parameter.

3.1 Future Plans

1. Complete installation of Drill-Pipe Rotation System and run a series of shake-down tests to commission this new system and make fully operational.

2. Finalize modifications to flow-loop piping around the Injection and Separation Towers in order to minimize the effects of connections on measurements of changes in weights of both towers during cuttings-transport tests.

3. Complete the design for a new system to vary elevation of the Flow Loop. Present this design at the next ABM in November and seek input from the JIP members. Finalize the design and obtain bids from qualified contractors to build and install the system.

Note: The purchase of a used crane mast is being considered. Therefore, the final design details are not expected until an appropriate mast is identified and purchased. This approach is preferred because it is expected that a better quality mast can be obtained for the same or less costs than what it would cost to design and build a new one.

4. DEVELOPMENT OF A FOAM GENERATOR/VISCOMETER FOR ELEVATED PRESSURE AND ELEVATED TEMPERATURE CONDITIONS (Task 9b)

Investigators: Mark Pickell, Troy Reed and Leonard Volk

OBJECTIVES

1. Develop a new instrument that will enable the generation of foams with a controllable bubble size and under elevated pressures and temperatures.

2. Develop a process that will enable measurements of the viscous properties of foams that are free of the influences of drainage (syneresis) and bubble coalescence and can quantify the effects of surface roughness on “wall slip”.

4.1 The Need for New Instrumentation and a Process

One of the important findings from Research Task #9, flow-loop tests with foam, is that bubble size has a primary effect on the apparent viscosity of a foam. This identified the need to have an instrument that can generate foam with a controlled bubble size and then measure its rheological properties. This has led to the development of a new concept for achieving these objectives. In particular, there is currently a need for an instrument that can generate a foam and measure its viscous properties. The instrument should be capable of controlling the following six variables independently. 1) foam quality (% volume of gas), 2) pressure, 3) temperature, 4) surfactants and other additives, 5) bubble size, and 6) surface roughness inside a viscometer. A survey of different manufacturers of viscometers and rheometers revealed that there is currently no commercially available instruments designed to accomplish the above list of measurements for foams.

As noted above the apparatus is termed a Foam Generator/Viscometer. It provides a means by which the rheology of foams, emulsions or other shear-sensitive media may be measured. Liquid components (such as surfactant and water) are selectively combined with a gas (such as nitrogen, air or other gases) in various ratios, mixed to a desired consistency, and allowed to flow under controlled conditions (pressure, temperature, and flow rate) through a modified (variable surface roughness) Couette-type rotary Viscometer at such a rate that the viscosity of the foam is determined while its properties (bubble size, quality, pressure, temperature, and viscosity) are maintained constant.

4.2 Progress – Foam Generator

The detailed design of a Foam Generator has been completed and is now being fabricated by Temco, Inc. The first prototype version will have an outer case that is made of clear plastic. The purpose is to enable visual observations of how well the foam circulates and how homogeneous it is. When it is concluded that the design is satisfactory, a stainless steel case will be built to house the Generator and enable the generation of foam at 1,500 psi and 300 F. It will then be used in tandem with the existing RS300 Thermo-Haake Rheometer that is also capable of operating at these same elevated pressures and temperatures.

4.3 Progress – Viscometer
Investigator: Aimee Washington (MS Student)

Project Title: "An Experimental Study of the Viscosity of Drilling Foam Using a Foam Generator/Viscometer"

Part of TASK 9b OBJECTIVES

- Discover a method of applying a uniform rough surface to the inside of the cup and the outside of the rotor in a Couette-type Viscometer.
- Discover a way to quantify the rough surface.
- Calibrate the RS300 rheometer that will be used for viscosity measurements.
- Conduct preliminary tests using commercially available foams.
- Connect the Rheometer and Foam Generator, develop the procedures that are necessary to control bubble size, and measure the viscous properties of a foam under controlled pressure and temperature conditions.

Summary of Problem

A Thermo-Haake RS300 Rheometer has been selected to measure the viscosity of foams. This rheometer was chosen because it has three essential features. It is designed to: 1) allow flow through the pressurized viscometer cup, 2) operate at pressures up to 100 bars (1500 psi), and 3) at temperatures up to 150 C. It is a Couette type of viscometer with rotors that turn inside a stationary cup.

Part of the research plan is to fabricate up to 4 additional rotors and cups with different amounts of roughness machined onto their surfaces. The purpose is to investigate how this affects the "slip" of foam at a solid boundary. It is known that when slip occurs within a viscometer, the viscosity of a foam will be underestimated because it shears less than a fluid that has no wall slip.

Another factor that is different for a foam compared to conventional liquids is that a foam tends to fill the space between the cup boundaries and the internal rotor. The RS300 is designed to test conventional liquids that are placed in the pressurized cup cell to a level that is only slightly above the rotor. At the top end of the rotor, there is a round magnet that is rotated by an external magnetic drive system. The clearance between the lid to the cup and this rotor magnet is relatively small. When foam fills this space it adds additional drag on the rotor. The purpose of calibrating this device with one or more calibration fluids, that have a certified viscosity, is to correct for end effects and bearing drag. Since the standard calibration fluids are liquids that do not slip at the solid boundaries, they provide corrections that are too high compared to a foam, if the foam is allowed to slip above and below the gap between the wall of the cup and the outer surface of the cylindrical rotor, the primary measurement area. For this reason, the internal surfaces above and below the rotor must have a surface roughness that will not allow wall slip for any of the foam test conditions.

Project Status:

Literature Review	Coatings	100%
	Surface Measurement	100%
	Rheometer/Viscometer	80%
	Foams	50%
Coatings	Machining	40%
Surface Measurement Instruments		100%
Calibration	#1 Canon Standardized Oil – 9.493 cP	100%
	#2 Canon Standardized Oil – 51.92 cP	100%
	#3 Cannon Standardized Oil – 108.3 cP	100%
Foam test on DTF flow loop		10%
Foam Generator	Not yet available, but prototype is designed and is now being made.	60%
Reports	ACTS Progress Repts.	100%
	Final	10%

Current Work

A relatively large roughness for the surfaces above and below the rotor has been selected and is being machined inside the four additional cups. In addition, different values of surface roughness are being machined on the sidewall of each cup and rotor, i.e., the surfaces that face each other to form the gap, which constitutes the primary measurement area for determining viscosity. The advantage of machining the roughness is that it maintains the gap clearance between the cup surface and the rotor's cylindrical surface. In addition, it is easier to achieve a uniform roughness on all of the surfaces. This work is currently being done by A-1 Machine Shop in Bristow, OK.

In order to make productive use of time, the RS300 Rheometer was connected to the small-scale Dynamic Test Facility flow loop. Some minor adjustments were made to the small flow loop in order to accommodate the attachment of the rheometer and enable reading of the pressure sensors. The initial tests indicate a foam viscosity of around 50 cP is generated in the DTF at pressures less than 100 psi and ambient temperatures. The tests are continuing in order to develop standard test procedures.

4.4 Future Plans

Since the Foam Generator will not be available until later in the year, the DTF will be used as a foam generator at low pressures and ambient temperatures.

1. The DTF will be used to generate and test foam under ambient conditions with varying degrees of surface roughness on the cup and rotors.

2. The two remaining cup and rotor sleeves will have rough surfaces applied in the amount indicated by the results from experiments with the 0.025 in. and 0.010 in. roughnesses.

3. These cups and rotors will be used to measure foam viscosities and to define how viscosity measurements are affected by surface roughness.

4. The next step will be to switch to the new Foam Generator when it becomes available. At that time, the initial tests will focus on repeating the data obtained with the DTF.

5. The final step will be to generate a foam with the Foam Generator that is identical to or at least very similar to what is observed in the ACTF. The corresponding viscosity data will then be used in a hydraulics model to compute frictional pressure drops and compare predictions from the model with ACTF test data for both the pipe sections and the annular section.

Deliverables

1. Quantify the effects of surface roughness on the viscosity measurements for an under-balanced drilling foam.

2. Develop standardized procedures for obtaining accurate measurements for the viscosity of foam, regardless of its constituents.

5. STUDY OF CUTTINGS TRANSPORT WITH AREATED MUD UNDER ELEVATED PRESSURE AND TEMPERATURE CONDITIONS (TASK 10)

Investigator: Lei Zhou (Ph.D. Candidate)

OBJECTIVES

1. Develop two-phase flow model for aerated fluids at elevated pressure and temperature inside annuli in a horizontal position without pipe rotation.

2. Determine experimentally the cuttings transport ability of aerated fluids under elevated pressure and temperature conditions.

3. Determine the gas/liquid flow rates for effective cuttings transport.

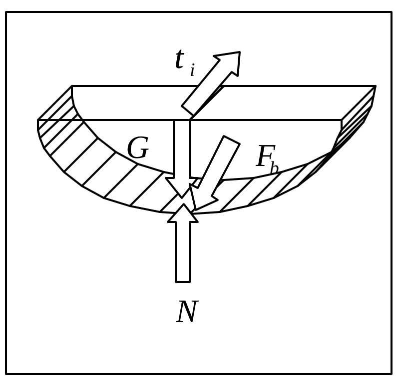
4. Develop a computational tool to calculate pressure losses with aerated fluids flowing under elevated pressure and temperature conditions.

Current Modeling Studies

The fact that the cuttings bed may or may not move at the bottom of the annulus must be accounted for. In the static case, the friction force, F_b is always equal to the driving force until the bed is about to move.

$$F_b = h_s N$$

where h_s is the static dry friction factor and N is the normal force on the wall produced by the weight of the cuttings bed. Looking at a small segment of the cuttings bed, the force analysis is as follows:



Doran[1] suggests the normal force, N, consists of two components. One is due to the submerged weight of solid particles, N_W, and the other is due to the transmission of the normal stress that results from the shear stress acting on the bed-suspension interface, N_F. The common way to calculate the apparent weight component for slurry flow, N_W, is as follows:

$$N_w = 0.5(r_s - r_L)gC_bD^2\left[\left(\frac{2y_b}{D}-1\right)\left(q_b+\frac{p}{2}\right)+\cos q_b\right]$$

Bagnold[2,3] (1954, 1957) showed that when a fluid flows over a deposit of solid particles, there exists the additional normal force, N_f, at the interface that is associated with the shear stress exerted by the fluid on the bed.

$$N_f = \frac{t_i S_i}{\tan f}$$

Where f is the angle of internal friction. The value of tanf varies between 0.35 and 0.75 according to the type of flow and particle characteristics; t_i is the interfacial shear stress.

If the cuttings bed starts to slide at the bottom of a pipe wall, and it is assumed that the friction coefficient, ?, is constant for a given solid, then F_{bm} is calculated by:

$$F_{bm} = h\left(N_w + N_f\right),$$

$$F_{bm} = h\left\{0.5(r_s - r_L)gC_bD^2\left[\left(\frac{2y_b}{D}-1\right)\left(q_b+\frac{p}{2}\right)+\cos q_b+\frac{t_iS_i}{\tan f}\right]\right\}$$

If the total driving force acting on the cuttings bed is less than the static dry friction force, the cuttings bed will not move.

$$A_{sb}\frac{dp}{dx}+F_{sl}+t_iS_{sl-bed} \le F_b$$

Otherwise, the bed will move and a dry friction force F_{bm}, will act between the pipe wall and a cuttings bed. In the case of an annulus, contact between the bed and the inner pipe will also affect this force balance. In either case, this is the basic mechanism that determines whether a bed moves or not.

Taitel and Dukler[4] developed a mechanistic model in 80's to predict the flow pattern of two-phase flow in pipes. Their model is applicable for steady-state, fully developed, Newtonian flow. The model was successfully tested against data collected in mainly small-diameter pipes under low pressure conditions and is widely used in the petroleum industry. More work is needed for larger diameters, annular geometries and high pressure flow.

As part of this project, a visual basic program is being developed to predict the frictional pressure loss in horizontal annuli. The start point of the two-phase (gas/Newtonian liquid) model is equilibrium stratified flow. It is assumed that the flow pattern is stratified and the necessary flow variables, such as liquid level in the annulus, are known. Then a Kelvin-Helmholtz stability analysis is conducted to determine whether or not the flow configuration is stable. If it is stable, stratified flow occurs. If not, a change to non-stratified flow occurs, and the resulting flow pattern is determined. After the flow pattern is found, the frictional pressure loss can be calculated based on the appropriate flow pattern.

Experiments on Aerated Fluids without Cuttings

Experiments on aerated fluids without cuttings have been conducted at EPET in the ACTF. Gas and liquid have been injected at different flow rates. Several parameters were measured during these tests. They include: temperature, differential pressure, mixture density in the annulus, and liquid holdup. The test points that have been run are listed in Table 5.1

T(F^0) / P(psi)	80		150		180	
	Qg (SCFM)	Ql (GPM)	Qg (SCFM)	Ql (GPM)	Qg (SCFM)	Ql (GPM)
100	60	100	100	100	120	100
200	60	150	100	150	120	150
300	60	200	100	200	120	200
400	60	250	100	250	120	250

Table 5.1 Aerated Fluids Tests without Cuttings

The LabView® data acquisition system can collect data every second. Because of the multiphase flow conditions, there are some fluctuations in the differential pressure data. Figure 5.1 is a sample of raw differential pressure data recorded from the test section of ACTF. Obviously, it is difficult to find the relevant information from the data. A data evaluation procedure is needed to help interpret and understand these measurements.

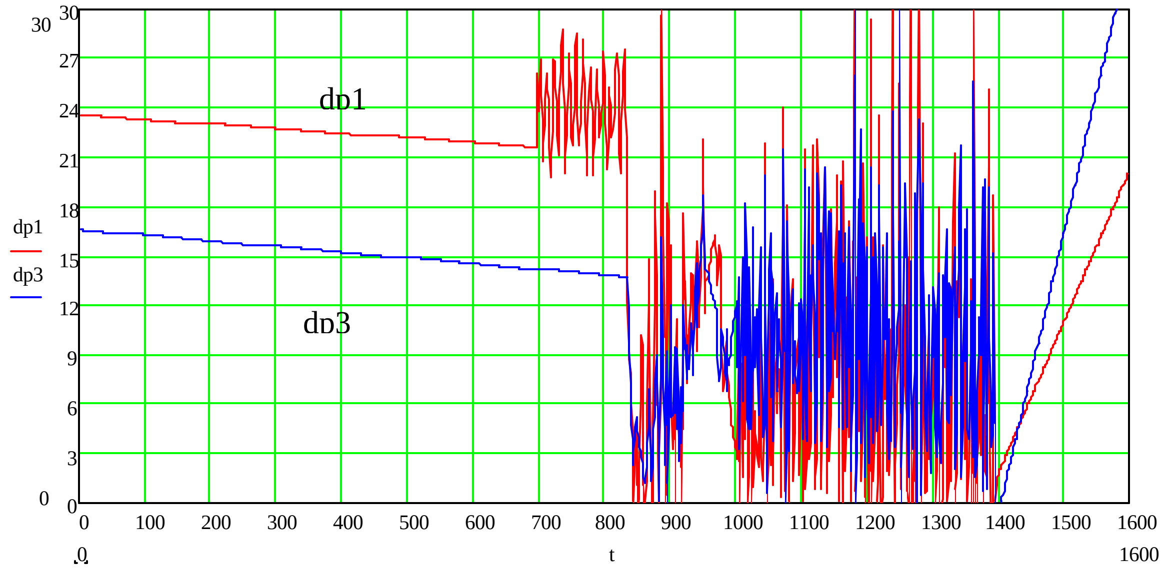


Figure 5.1 - Raw Differential Pressure Data from LabView Collection

In Figure 5.1, dp1(inches H_2O) is the differential pressure measured in the 4-inch pipe, and dp3(inches H_2O) is differential pressure measured in the annular section.

A Mathcad2001 program is being applied to smooth the raw data and extract the usable information. The local averaging program, that is part of MathCAD, returns an *m*-element vector created by the piecewise use of a symmetric *k*-nearest neighbor linear least square fitting procedure in which *k* is adaptively selected. Figure 5.2 is an example of the smoothed data plot.

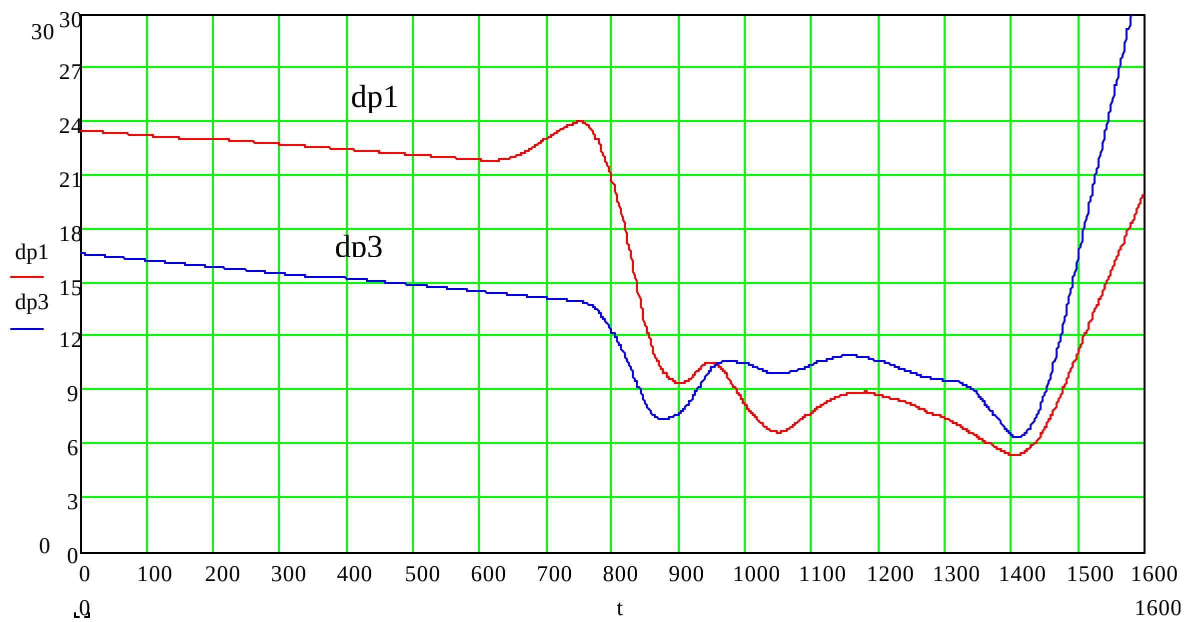


Figure 5.2 - Smoothed Differential Pressure Data

Experiments on Cuttings Transport with Aerated Fluids

Experiments on cuttings transport with aerated fluids have been conducted at EPET. A total of 24 tests have been run from the planned test matrix. Some data points were repeated. Tables 5.2 and 5.3 show the matrix of tests that have been conducted thus far.

T(F^0) / P(psi)	80		120		150		180	
	Qg (SCFM)	Ql (GPM)	Qg (SCFM)	Ql (GPM)	Qg (SCFM)	Ql (GPM)	Qg (SCFM)	Ql (GPM)
100	60	100	80	100	100	100	120	100
200	60	150	80	150	100	150	120	150
300	60	200	80	200	100	200	120	200
400	60	250	80	250	100	250	120	250

Table 5.2 - Cuttings Transport with Aerated Fluids (ROP = 30 ft/hr)

T(F^0) / P(psi)	80		120	
	Qg (SCFM)	Ql (GPM)	Qg (SCFM)	Ql (GPM)
100	60	100	80	100
200	60	150	80	150
300	60	200	80	200
400	60	250	80	250

Table 5.3 - Cuttings Transport with Aerated Fluids (ROP = 50 ft/hr)

The cuttings injection system has been improved. The desired injection rate can be achieved by adjusting the injection auger speed. Figure 5.3 shows the weight change of the injection tower with respect to time.

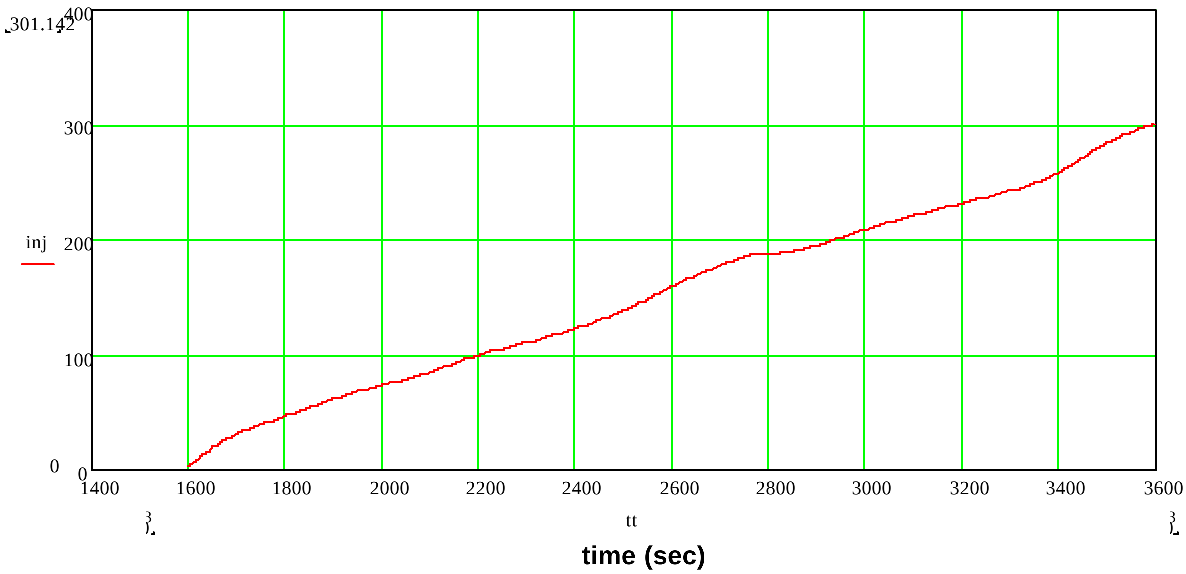


Figure 5.3 - Weight Change of Injection Tower (lbm) vs Time (sec)

The experiments on cuttings transport with aerated fluids were conducted at elevated temperatures and elevated pressures. The test temperatures are from 80^{o}F to 180^{o}F. Experimental pressures range from 100 Psi to 400 Psi. Three different cases are observed during the tests.

<u>Case1</u>: Noticeable pressure drops are observed when a cuttings bed is formed in the test sections. Figures 5.4 and 5.5 display the raw data collected by LabView and the corresponding smoothed data from MathCAD2001®, respectively. The test gas flow rate is 80SCFM, and the liquid flow rate is 100 GPM. The pressure is 100 Psi, and temperature is 120^{o}F. When the cuttings bed is fully formed and stable, the differential pressure curve tends to be flat. Because of the configuration of the flow loop, cuttings will deposit in the annulus first at low flow rates. During this time, the differential pressure in the 4-inch pipe is constant and unchanging.

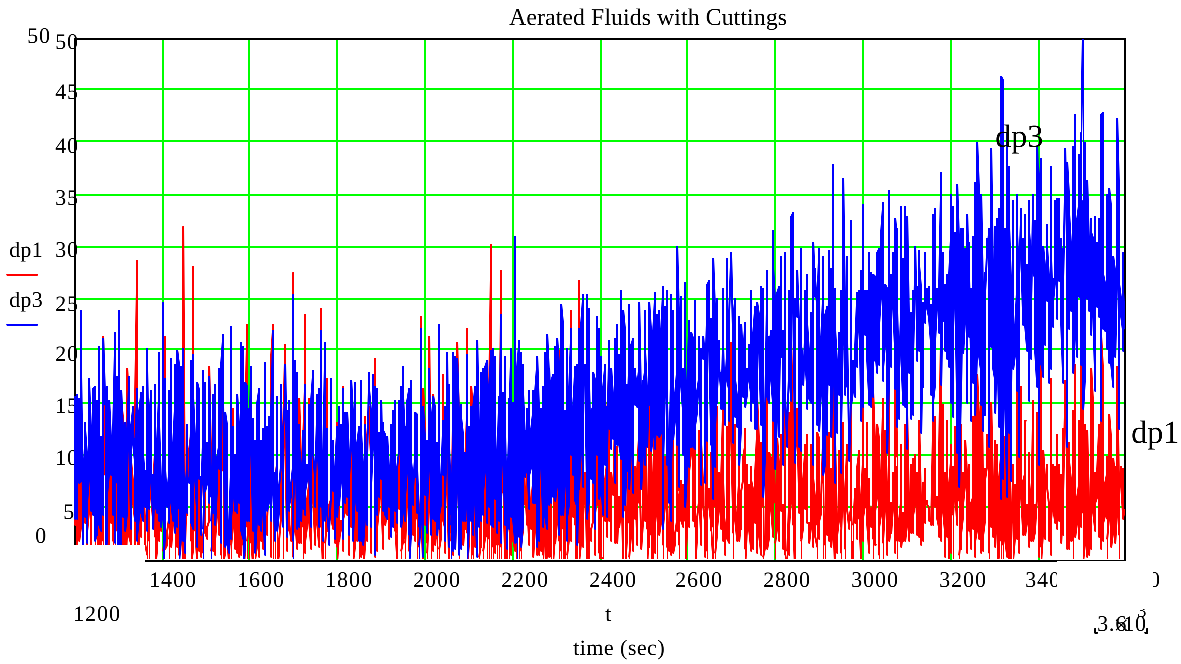


Figure 5.4 - Differential Pressure of Aerated Fluids with Cuttings in Annuli and 4'' pipe

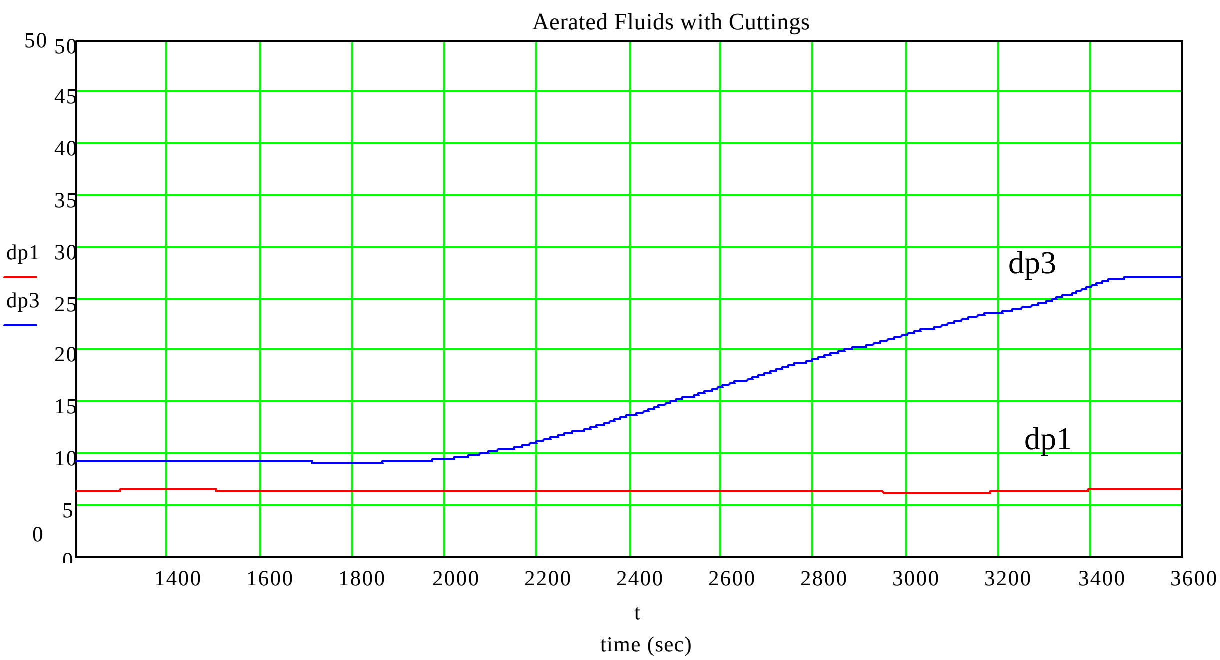


Figure 5.5 - Differential Pressure of Aerated Fluids with Cuttings

Figure 5.6 shows readings from the nuclear densitometers when the three-phase mixtures are captured in the annular test section. Dc1 is the densitometer that is installed at the end of the test section. Dc2 is the densitometer that is installed near the middle of the test section.

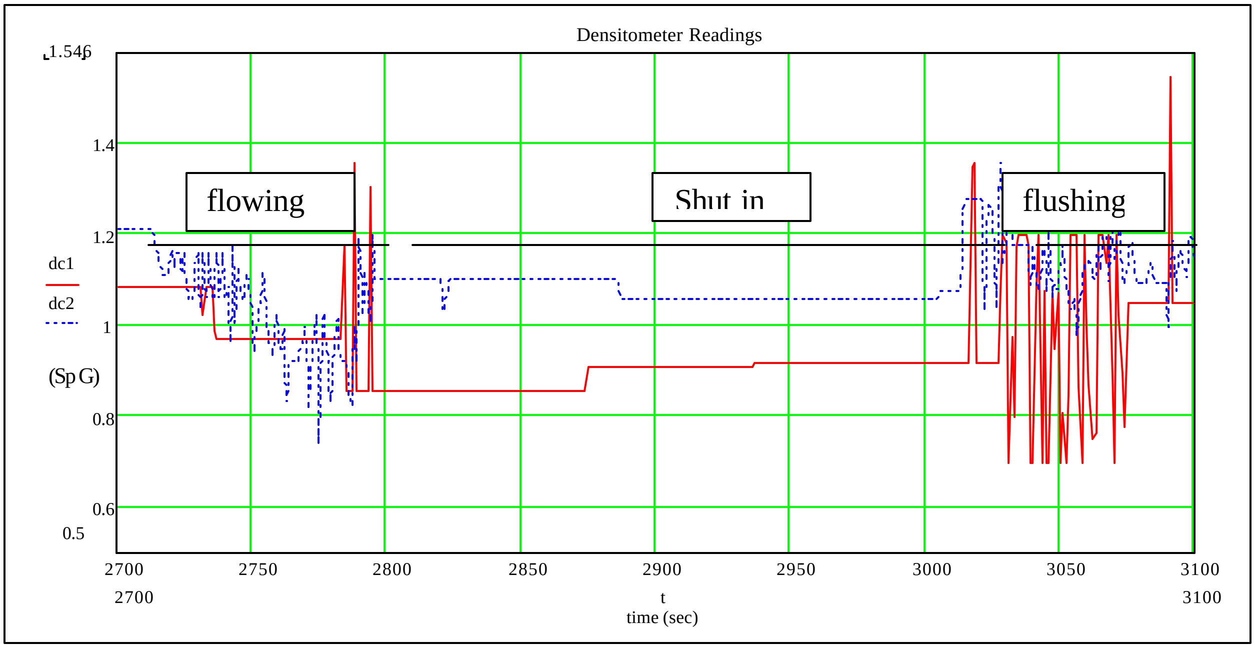


Figure 5.6 - Densitometer Readings

Case 2: An intermediate condition is observed when the flow rate is not high enough to suspend all of the cuttings and does not allow the cuttings to deposit in the annular section first. At these intermediate flow rates, cuttings also deposit in the 4-in pipe at the same time, and the DP curves in the annulus and 4-inch pipe both have an inclined shape. Figure 5.7 shows an example of the DP curves with respect to time.

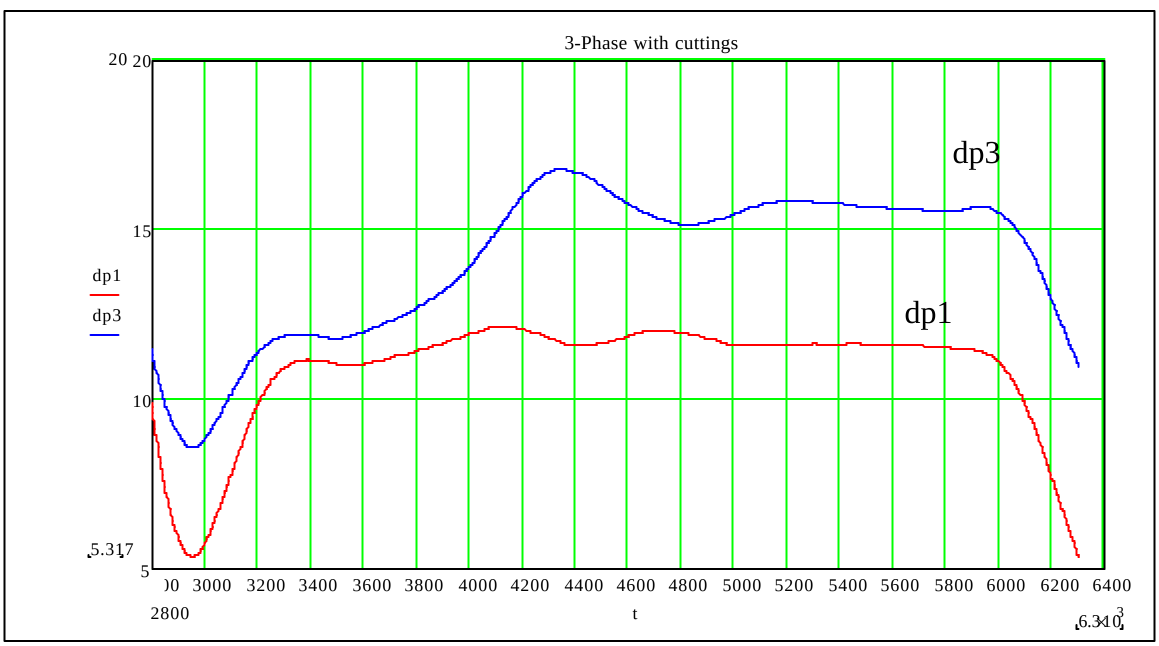
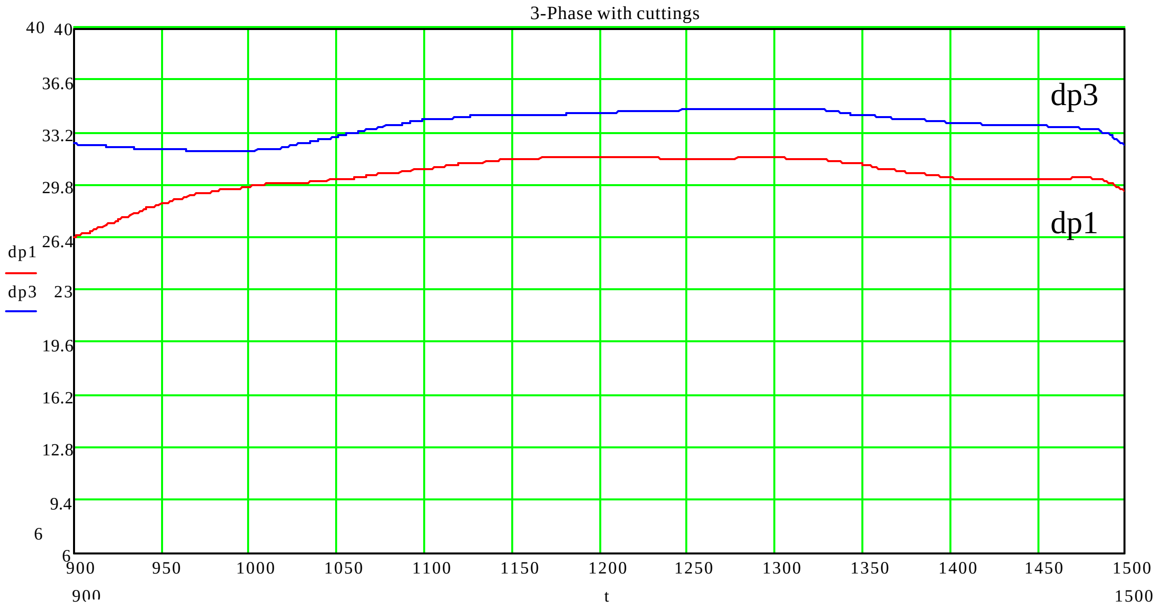


Figure 5.7 - Differential Pressure of Aerated Fluids with Cuttings

Case 3: When the liquid flow rate is increased to a certain value, the differential pressure curve displays different shapes. The cuttings no longer accumulate in the annulus. Also, the inclined shape of the DP curve is no longer observed in the annular section. Instead, a nearly constant value of DP is observed. This suggests that the injected cuttings may be completely suspended in the fluids, and there is no stationary cuttings bed formed in the test section. The cuttings flow with the aerated fluids as a slurry. Figure 5.8 shows an example of the DP curves for this case with respect to time.



time (sec)

Figure 5.8 - Differential Pressure of Aerated Fluids with Cuttings

When steady state flow is established, the differential pressure in the test section no longer changes. The multiphase measurement system is used to trap a sample of the three-phase mixture in the annular test section. Then, an air expansion tank can be used to help measure the volume of air captured inside the annular section. Nuclear densitometers measure the mixture density, which, in turn, can be used to back calculate the volumetric concentrations of each phase.

The cuttings volumetric concentration is calculated with a Visual Basic program that employs mass conservation equations and the gas equation of state. Using the annular pressure collected before and after expansion, and the mixture density from the nuclear densitometer, the solution of three equations can give the volumetric concentration of each phase trapped in the annulus. Since we assume the geometry of the annulus and porosity of the packed cuttings are known (from separate lab data), the cuttings bed height can also be calculated.

Figure 5.9 is the input/output interface of the VB program for calculating cuttings' concentrations.

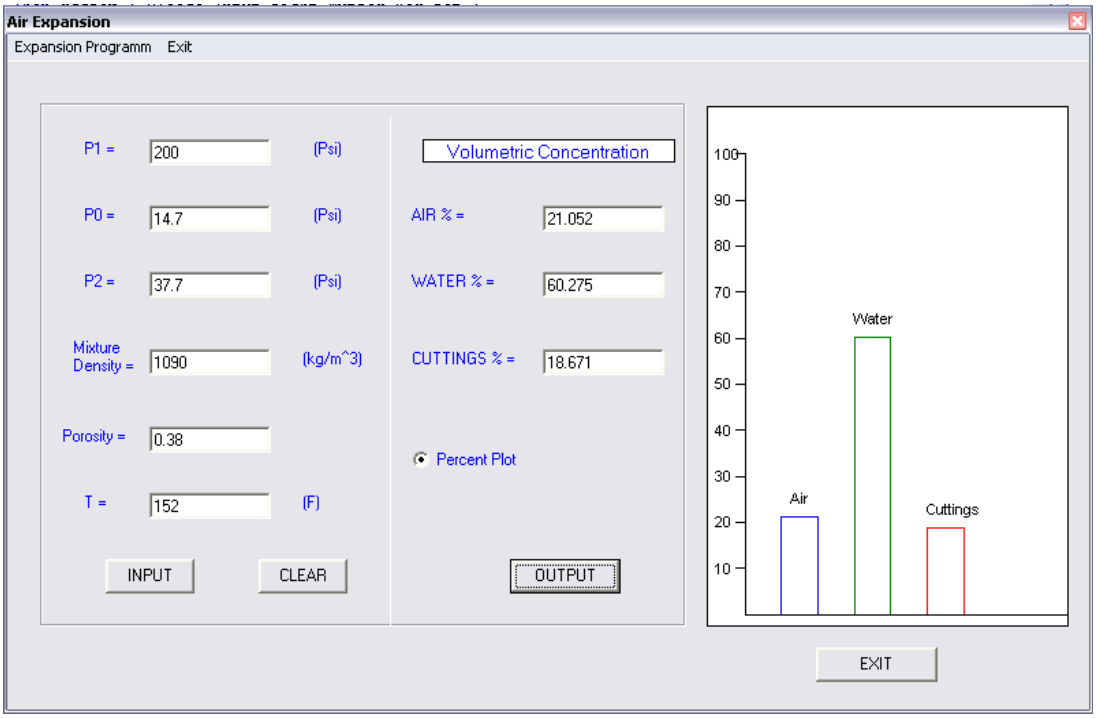


Figure 5.9 - Input/Output Interface of Expansion Program

Figure 5.10 shows the cuttings concentration at different liquid flow rate. The gas flow rate is 60 SCFM.

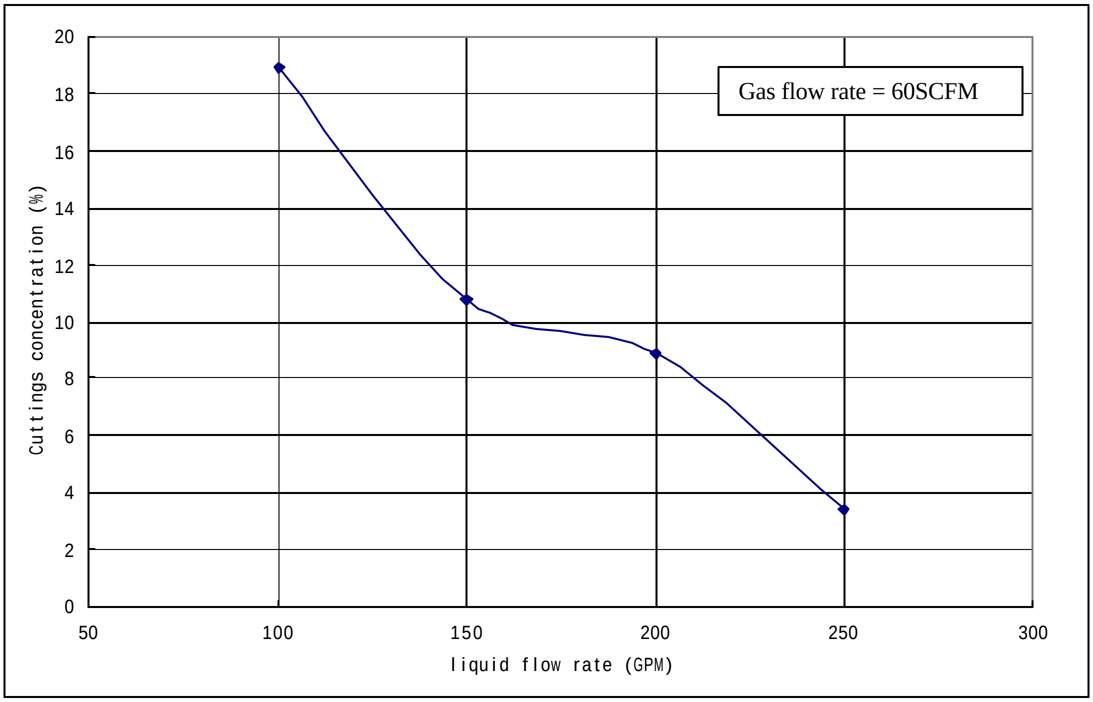


Figure 5.10 - Cuttings Concentration vs Liquid Flow Rate

The calculation results from the air expansion/densitometer reading are compared to the flush/weight results, which are obtained from the load cells' measurements. The flushing system is to flush the cuttings trapped in the annular section to the separation tower and take the weight measurement. How many cuttings are accumulated in the annulus can be determined. It has the same purpose as the air expansion/ densitometer measurements but a different way. Five data points are compared between those two methods shown on Table 5.4.

	Load Cell Measurement (Lbm)	Nuclear Densitometer Calculation (Lbm)	? (Lbm)	Difference (%)
1	251	254	3	1.20
2	317	309	-8	-2.52
3	221	94	-127	-57.47
4	273	168	-105	-38.46
5	106	103	-3	-2.83

Table 5.4 - Comparisons of Flush-Weight Data with Densitometer Calculations

The data points #1 to #4 in Table 5.4 were tested at the same flow conditions: The liquid flow rate was 150GPM; gas flow rate 80SCFM; pressure 200Psi; temperature 120 F; and a cuttings injection rate of 50 ROP. Point #5 corresponds to: 200GPM of liquid flow rate; 80SCFM of gas flow rate; 300 Psi and 120 F.

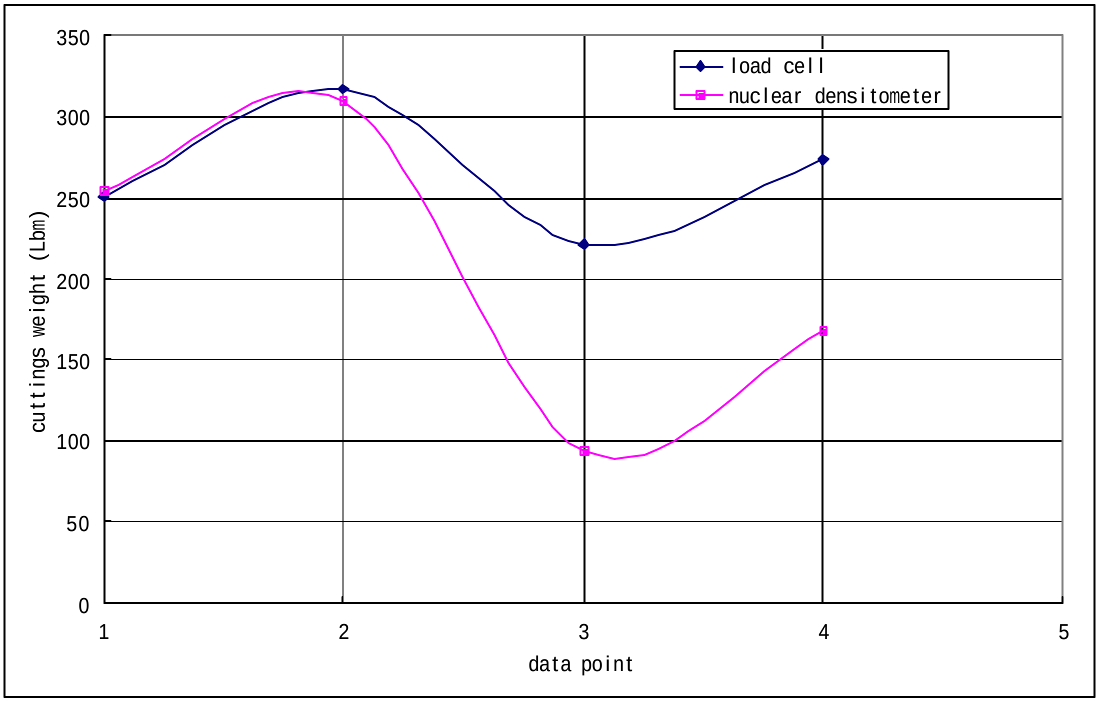


Figure 5.11 - Comparison of Flush/Weight Data with Densitometer Calculations

From Figure 5.11, there are differences between the load-cell measurements and nuclear densitometer measurements at points #3 and #4. The average value of load cell measurements is $\frac{251 + 317 + 221 + 273}{4} = 265.6$. The average value of the densitometer measurements is $\frac{254 + 309 + 94 + 168}{4} = 206$. The difference between them is about 60Lbm. If point #3 is taken off from the densitometer measurements, which is considered to be a "bad" data point, the average value of densitometer measurements is $\frac{254 + 309 + 168}{3} = 243.6$. Now the difference between those two methods is about 22 lbm. Which data set is more accurate is under evaluation. The consistency of weight measurements for cuttings in the annulus is questionable, since the deviation from the average value is about 17% for load cell measurements and 27% for nuclear densitometers measurements for the four repeated data points. Further modifications and testing of the collection/weighing system is needed to get consistent and accurate weight measurement of cuttings in the annulus.

Future Work

1. Continue air/water/cuttings three-phase tests at EPET conditions.
2. Any necessary loop modification.
3. Perform data analysis.
4. Continue development of the hydraulics model for cuttings transport.

Nomenclature

P	Pressure, Psi
T	Temperature, ^oF
D	Diameter, ft
F_{bm}	Frictional force when cuttings bed is moving, lbf
F_{SL}	Dry friction force contributed by the particles in the slurry
A	Area, ft^2
F	Frictional force, lbf
S	Wetting perimeter, ft
g	Gravitational acceleration, ft/s^2
C_D	Drag coefficient
G	Gravitational force, lbf
$N_?$	Additional normal force, lbf
N_w	Apparent weight, lbf
C_b	Cuttings bed concentration,
P_1	Annular section pressure before expansion, Psi
P_0	Air expansion tank pressure before expansion, Psi
P_2	Air expansion tank pressure after expansion, Psi

Greek Letters

r	Density, lbm/ft^3
t	Shear stress, psi
h_s	Static dry friction factor
f	Angle of internal friction
h	Dry frictional factor

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6. STUDY OF CUTTINGS TRANSPORT WITH FOAM UNDER ELEVATED PRESSURE AND ELEVATED TEMPERATURE CONDITIONS (Task 13)

Investigator: Zhu Chen

6.1 OBJECTIVES

1. Conduct an experimental investigation of foam rheology in pipes and an annulus under ETEP conditions.

2. Experimentally determine and numerically predict volumetric requirements for effective cuttings transport with foam in horizontal wellbores under EPET conditions, initially without pipe rotation.

3. Develop a mechanistic cuttings-transport computer simulator for foam under EPET conditions for down-hole drilling applications.

4. Verify an existing TUDRP computer simulator for foam hydraulics via comparisons with experimental data from the ACTS Flow Loop (ACTF).

<u>Recent Work</u>

The following tasks have been undertaken since April 2003:

- Continuation of literature review on foam flow and cuttings transport with foam.
- The experiment of temperature and pressure effect on viscosities of candidate foam base liquids has been conducted.
- Development of a hydraulics model for foam flow through an annulus.
- Research progress report preparation and presentation at the May ABM meeting.

6.2 Literature Review

A review of the relevant literature has continued since April 2003, and recent technical papers on foam rheology and cuttings transport with foam were included. Also, since bubble size, size distribution and shape have a significant effect on foam rheology and a foam generator and a viscometer are being developed to enable new studies of the effects of these parameters on foam rheology. A literature survey on bubble-size effects on foam rheology is also continuing. Three new papers on foam rheology were found. No papers on cuttings transport with foam were found. In addition, two relatively new papers on cuttings transport with conventional drilling fluids were found.

Kakadjian, et al. (1) studied HP/HT (pressure up to 50 bars and temperature up to 90 °C) rheology of aqueous compressible fluids using a re-circulating rheometer, which was designed, built and calibrated in the Institut Français du Pétrole. The re-circulating set-up allows the foam to circulate at a specific shear-rate condition until the structure is equilibrated. Also, a visualization cell coupled to an image-acquisition device permits characterization of the foam structure in parallel with the rheological measurements.

Rheological evaluations at several pressures, temperatures and foam qualities were investigated. The Specific Volume Expansion Ratio was used to determine the master curves of the rheological parameters. The three parameters of the Herschel-Bulkley rheological model were determined and then correlated to quality, pressure and temperature.

Khade, et al. (2) studied the rheology of foams with a guar-gum liquid phase. Experiments were carried out with guar gel and guar foam fluids using a 1/2-in. pipe viscometer at 1000 psi and temperature ranging from 100 to 200 °F. Guar, surfactant and nitrogen were used, respectively, as the gelling agent, foaming agent and gas phase. The study showed that both guar gel and guar foam fluids exhibit a behavior analogous to a Power-Law fluid. Based on their experimental data, they developed new correlations, which are functions of temperature, foam quality, shear rate, and fluid concentrations. They reported high apparent viscosities of foam fluids at high qualities.

Guo, et al. (3) developed a closed-form hydraulics equation for predicting bottom-hole pressure in UBD with foam. The analytical model couples the frictional and hydrostatic pressure components in vertical and inclined boreholes. Theoretical analyses with the model indicate that the injection Gas-Liquid Ratio (GLR) is a dominating factor affecting depth limit and ECD in stable foam drilling. The new model was used to generate depth limit and ECD curves that can be used for multi-gradient drilling on-shore and in deepwater drilling projects.

With regard to cuttings transport with foam, there are no papers on this specific subject, but there are two relevant papers on cuttings transport by Martins, et al. (4) and Kelessidis (5). Martins, et al. conducted a study on real-time monitoring of hole-cleaning during the drilling of a deepwater extended-reach well. They first utilized a cuttings-flow meter device located on a PETROBRAS-X platform during the drilling of an extended horizontal well (5211 m total depth) at 1212 m water depth. The measurements from the Cuttings Flow Meter (CFM) are presented in their paper. Kelessidis, et al. studied cuttings transport in horizontal and deviated wells during coiled-tubing drilling. The paper by Martins, et al. provides a critical review of the state-of-the-art on efficient cuttings transport during coiled-tubing drilling. In addition, they discuss the critical parameters involved (such as minimum suspension velocity) and establish the expected range of each parameter.

With respect to bubble size distribution, David (6) studied foam bubble size distribution. The following is a summary of some of his results. In general, when a microscope is used for the determination of the bubble size distribution, the result is given in terms of the number of particles N of size r. The distribution function is FN , and

Therefore, for the total number No of bubbles counted, $d\left(\frac{N}{N_0}\right) = f_N(r)dr$, which, when normalized, results in: $\int_0^{\infty} f_N(r)dr = 1$.

The mean bubble diameter can be based on three parameters: diameter, area, and volume. The use of each of these parameters on its importance to the question of interest. The three mean diameters are defined by David (6) as follows:

(A) mean diameter: $d_m = 2r_{ol} = \frac{\int_0^{\infty} 2rf_N(r)dr}{\int_0^{\infty} f_N(r)dr}$

(B) mean surface diameter : $d_m = 2r_{os} = \left[\frac{\int_0^{\infty} (2r)^2 f_N(r)dr}{\int_0^{\infty} f_N(r)dr}\right]^{\frac{1}{2}}$

(C) mean volume diameter: $d_m = 2r_{ov} = \left[\frac{\int_0^{\infty} (2r)^3 f_N(r)dr}{\int_0^{\infty} f_N(r)dr}\right]^{\frac{1}{3}}$

In most cases, the mean diameter in category A can be calculated by:

$d_m = \frac{\sum n_i d_i}{\sum n_i}$, where n_i is the number of bubbles of diameter d_i.

The standard deviation S_d, for the arithmetic mean based on the diameter is given by:

$$S_d = \sqrt{\frac{\sum n_i d_i^{\,2}}{\sum n_i} - \left(\frac{\sum n_i d_i}{\sum n_i}\right)^2} \quad .$$

It is possible to characterize the distribution of bubble size or dispersion by using the following ratio: $\frac{d_m}{\sqrt{2S_d}}$; a zero value indicates that there are no two bubbles of the same diameter and an infinite value would indicate that all the bubbles have the same diameter.

The average bubble diameter with respect to quality was obtained, and also the Weibull distribution was modified to apply for the cumulative distribution of bubble size distribution. He finally derived a bubble size cumulative distribution function D(d) as $D(d) = 1 - \exp\left[-\frac{d}{0.344}\right]^{2.1}$, which is a function of foam quality (gas vol. / foam vol.).

J.R. Calvert and K. Nezhati (7) studied the relation between bubble size and foam rheology. Although the foam rheology model used by these authors is not common, their approach may be illuminating in studies of bubble size and foam rheology. They used a 4-parameter model, involving yield stress τ, consistency index k, flow index n and thickness of the slip layer δ. This model provided good correlations of the measured data by assuming the values of K=2.5 and n=0.4 for all foams tested. They only sought relationships between average bubble size, yield stress, slip-layer thickness and expansion ratio. Experimentally they found that yield stress went through a minimum at an expansion ratio of about 4, which may be related to the transition between polyhedral/spherical bubble shapes. Furthermore, the authors report that yield stress decreases with bubble size, but from their data it can be seen that the correlation is not strong. Finally, they did not derive quantitative correlations between bubble size and foam rheology.

6.3 EXPERIMENTS

6.3.1 Testing of Temperature Effects on Foam Base Fluids

Polymers were used in two foam formulations for this research. Formulation A consists of 5g foaming agent + 1.25g Xanthan (polymer) + 0.5g PAC (polymer) 495g water + 0.25 NaCl (pH=9), and Formulation B contains 5g foaming agent + 1g Xanthan (polymer) + 495g water + 0.25 NaCl (pH=9). Previous foam experiments at TUDRP have not included polymers. It is necessary to characterize the rheology of base fluid over a range of pressure and temperature, and then study the relationship between foam properties and the base-fluid properties. For example, a more viscous base fluid will reduce the rate of drainage from a foam and increase its stability.

A Chandler Model 3500LS Viscometer was used to measure viscosity of the two candidate foam base fluids with varying temperature. Temperature was increased from 80 to 200 ^{o}F. The data are shown in Figures 6.1 and 6.2. The experimental data show that the 600 RPM readings for the two base fluids are reduced by 1/2 when temperature increases from 80 to 200 ^{o}F, and the 3 RPM readings are reduced by 80% or even more.

Figure 6.1 - Viscometer Readings with Varying Temperature of Foam Base Fluid Formulation B

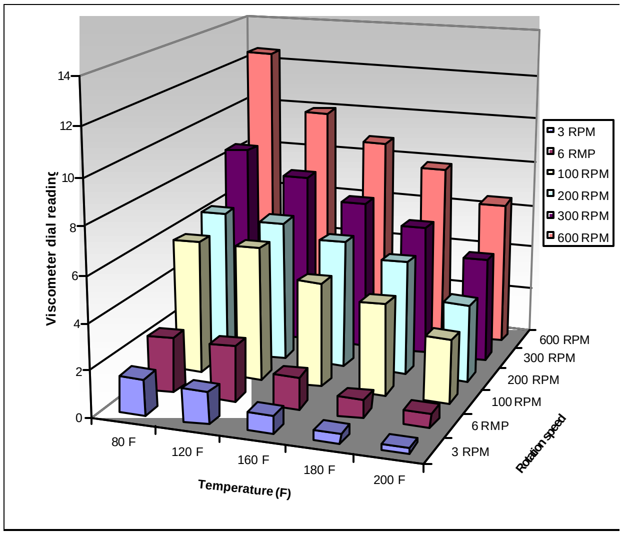
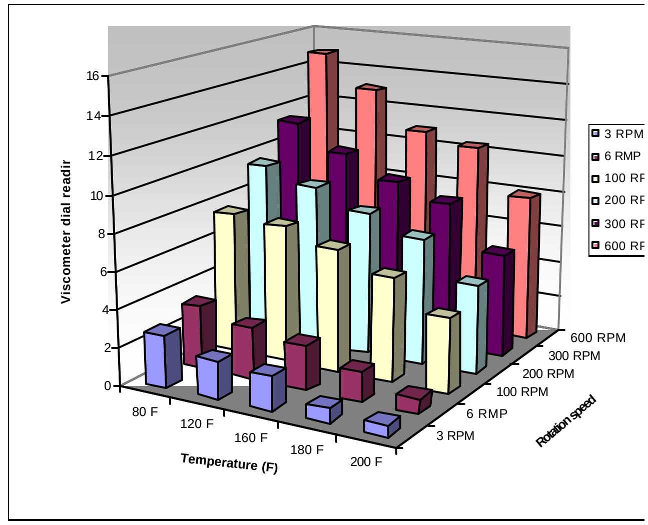


Figure 6.2 - Viscometer Readings with Varying Temperature of Foam Base Fluid Formulation A



6.3.2 - Tests of Pressure and Temperature Effects on Foam Base Fluids

Experiments that combined the effects of pressure and temperature on foam base fluids were also conducted with the Fann75 Viscometer. As stated in the previous quarterly report, the viscometer was originally installed with F1.0 spring, which is suitable for measuring high viscosity fluids, but since the viscosities of the foam base liquids are relatively low, an F0.2 spring module was purchased and installed. The F0.2 torsion spring was first calibrated with a 20 cP calibration fluid from Brookfield Engineering Laboratories, Inc. Figure 6.3 shows the calibration chart.

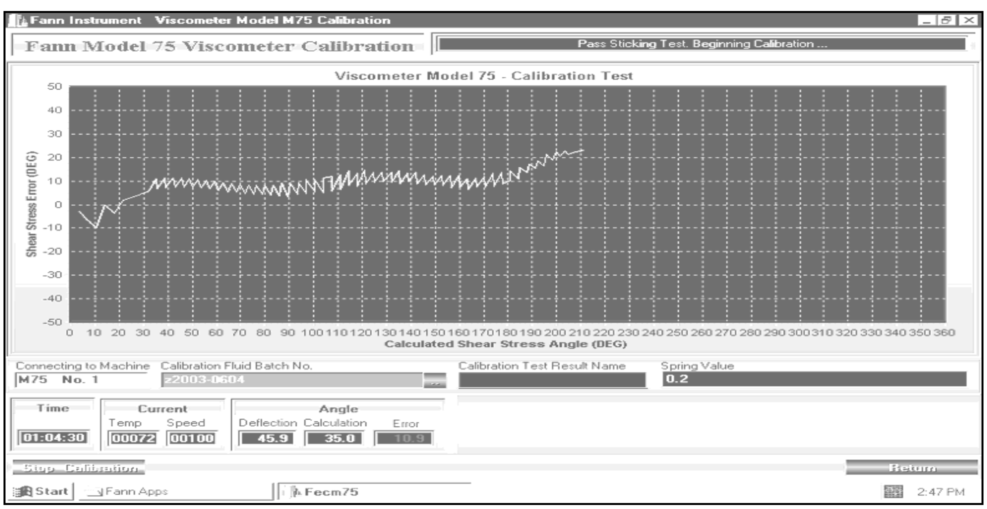


Figure 6.3. - Calibration Chart for the Fann75 F0.2 Spring Module

After calibration, the foam base liquids were tested with the Fann 75 Viscometer. The effects of pressure and temperature on foam base-liquid B is shown in Table 6.1 and Figure 6.4. Based on the test results, it is shown that temperature effect is significant, while the effects of pressure are very small over the range of these tests.

Table 6.1 - Fann 75 HPHT Rotational Viscometer Test Results

Temperature (°F)	Pressure (psi)	Viscosity (cp)
74.7	0	7.9
75.3	1104	8.1
75.3	1908	8.46
174.8	25	5.88
169.2	1047	6.02
162.8	1977	6.16
231.6	3678	2.04
232.4	1133	1.92
232.9	2096	1.86

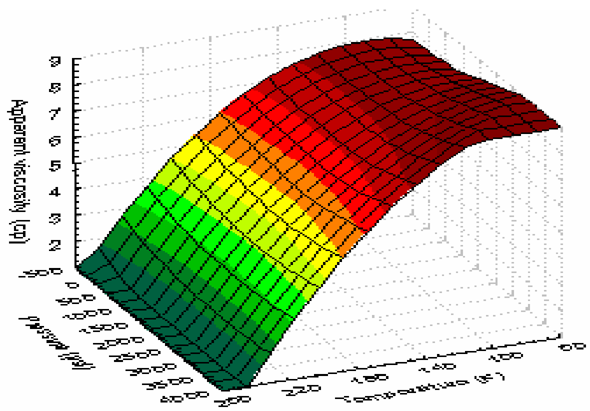


Figure 6.4. - Temperature and Pressure Effect on Foam Base Liquid

6.4 Development of a Hydraulic Model for Foam Flow in an Annulus

A number of models have been developed for foam hydraulic calculations in the past three decades. These include models developed by Blauer, et al (10)., Sanghani, (11), Beyer, et al.(12), Valko and Economides, (13) Gardiner, et al. (9), Lourenco, (14) and most recently by Guo, et al. (3). These earlier models for foam hydraulics are focused mainly on pipe flow. But for practical drilling application, a hydraulics model for the flow of foams through annuli is also needed. For this reason, a hydraulics model for flow of a Power-Law foam through a concentric annulus has been developed. The proposed model is based on the work of Fredrickson and Bird (8) and Gardiner, et al. (9). In

addition, the Volume Equalized Principle of Valko and Economides is used, and wall-slip effects are considered in the new model that is discussed next.
The major assumptions of this model are: steady state and isothermal foam flow, ignoring the convective acceleration components, and use of the same slip velocity at the outer casing and inner pipe.

The final equation for this model is as follows.

$$Q = \frac{np R^3}{1+3n}\left(\frac{R \cdot e^{n-1}}{2K_{ve}} \cdot \frac{dP}{dL}\right)^{\frac{1}{n}}\left[\left(1-l^2\right)^{1+\frac{1}{n}} - s^{1-\frac{1}{n}}\left(l^2 - s^2\right)^{1+\frac{1}{n}}\right] + p \cdot R^2\left(1-s\right) \cdot V_{slip}$$

The value of ? to be used in this equation can be computed by using the following relationship.

$$\int_s^l \left(\frac{l^2}{x} - x\right)^{\frac{1}{n}} dx - \int_l^1 \left(-\frac{l^2}{x} + x\right)^{\frac{1}{n}} dx = 0$$

For given numerical values for n and s, the ? values can be computed. Then a table can be constructed which contains n, s, and ? values. These values of ? can be used with the first equation to compute Q, if dP/dL is known, or compute dP/dL, if Q is given. These equations are valid for arbitrary values of n and s. A detailed derivation of this model is given in Appendix A.

6.5 Future Work

The main future tasks include:

1. Conduct foam rheology studies with the new Foam Generator/Viscometer, which is being developed as part of Task 9b.
2. Conduct flow loop tests with the ACTS Flow Loop from the fall of 2003.
3. Compare the foam hydraulics model developed by Evren Özbayoglu with experimental data; then decide whether to develop a new model or improve this existing cuttings-transport model.

6.6 References

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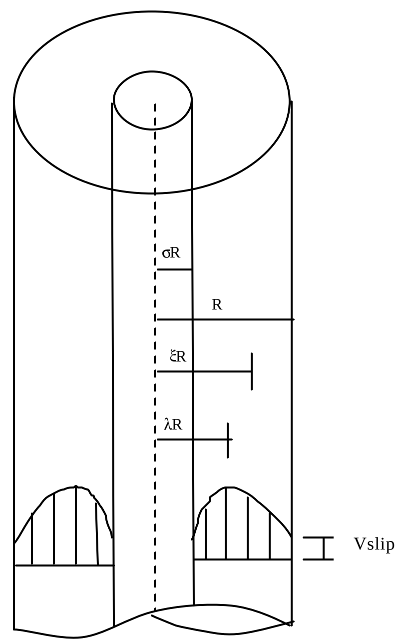
Appendix A Derivation of Hydraulic Model for Foam Flow in Annulus

The key feature of this model is to combine the Volume Equalized Power-Law rheological model with the proper momentum conservation equation; and then derive a function, which can not be integrated with traditional methods, in order to get an analytical solution. Several steps of integration and manipulation are necessary in order to obtain a solution for foam flow in an annulus.

Figure 6.5. - Schematic of Axial Flow of Foam thru a Concentric Annulus



From Figure 6.5, we assume the same slip velocity, Vslip, at the outer casing and inner pipe. The stress distribution for axial laminar flow of an arbitrary inelastic non-Newtonian fluid through a concentric annulus is known to be:

$$t = \frac{dP}{dL} \cdot \frac{R}{2}\left(x - \frac{l^2}{x}\right) \qquad (1)$$

Where $x = \frac{r}{R}$, and ? corresponds to the dimensionless radius of the maximum velocity in the annulus. It is a constant that has to be determined later, but we can first regard it as a: "constant of integration".

The Volume Equalized Power-Law rheological model is given by,

$$t = K_{VE} \times e^{1-n}\left(\frac{du}{dr}\right)^n \qquad (2)$$

When Eqn. 2 is combined with Eqn. 1 and formally integrated, one obtains,

(note: $dr = R \cdot dx$)

$$u_i = R\left(\frac{R \cdot e^{n-1}}{2K_{ve}} \cdot \frac{dP}{dL}\right)^{\frac{1}{n}} \int_s^x \left(\frac{l^2}{x} - x\right)^{\frac{1}{n}} dx + V_{slip} \qquad s \le x \le l \qquad (3)$$

$$u_o = R\left(\frac{R \cdot e^{n-1}}{2K_{ve}} \cdot \frac{dP}{dL}\right)^{\frac{1}{n}} \int_x^1 \left(-\frac{l^2}{x} + x\right)^{\frac{1}{n}} dx + V_{slip} \qquad l \le x \le 1 \qquad (4)$$

Note that the boundary conditions used here are:

$$u_i(x = s) = V_{slip} \quad and \quad u_o(x = 1) = V_{slip}$$

Then the constant ? is determined by requiring Eqn. 3 and Eqn. 4 be equal at the location of the velocity maximum. This gives at once:

$$\int_s^l \left(\frac{l^2}{x} - x \right)^{\frac{1}{n}} dx - \int_l^1 \left(-\frac{l^2}{x} + x \right)^{\frac{1}{n}} dx = 0 \qquad (5)$$

This relation gives ? as a function of the geometrical quantity “s” and the Power-Law flow behavior index “n”.

The volume rate of flow is:

$$Q = 2p R^2 \left(\int_s^1 x \cdot u \cdot dx \right) \qquad (6)$$

If one introduces Eqn. 3 and 4 into Eqn. 6, the following is obtained

$$Q = 2p R^3 \cdot \left(\frac{R \cdot e^{n-1}}{2K_{ve}} \cdot \frac{dP}{dL} \right)^{\frac{1}{n}} \left\{ \int_s^l x \cdot dx \cdot \int_s^x \left(\frac{l^2}{x} - x \right)^{\frac{1}{n}} dx + \int_l^1 x \cdot dx \cdot \int_x^1 \left(-\frac{l^2}{x} + x \right)^{\frac{1}{n}} dx \right\} + p \cdot R^2 (1 - s) \cdot V_{slip} \qquad (7)$$

It can be shown that by interchanging the order of integration in the two iterated integrals in Eqn. 7, this leads to the following results.

$$I = \int_s^l x \cdot dx \cdot \int_s^x \left(\frac{l^2}{x} - x \right)^{\frac{1}{n}} dx + \int_l^1 x \cdot dx \cdot \int_x^1 \left(-\frac{l^2}{x} + x \right)^{\frac{1}{n}} dx = \int_s^l \left(\frac{l^2}{x} - x \right)^{\frac{1}{n}} dx \cdot \int_x^l \cdot x \cdot dx + \int_l^1 \left(-\frac{l^2}{x} + x \right)^{\frac{1}{n}} dx \cdot \int_l^x x \cdot dx$$

$$= \frac{1}{2} \int_s^l \left(l^2 - x^2 \right) \cdot \left(l^2 - x^2 \right)^{\frac{1}{n}} \cdot x^{-\frac{1}{n}} dx + \int_l^1 -\left(l^2 + x^2 \right) \cdot \left(-l^2 + x^2 \right)^{\frac{1}{n}} x^{-\frac{1}{n}} dx = \frac{1}{2} \int_s^1 \left| l^2 - x^2 \right|^{1+\frac{1}{n}} x^{-\frac{1}{n}} dx \qquad (8)$$

Integrating by parts the integrals in Eqn. 7 and Eqn. 8, and adding those two equations together:

$$I = \frac{1}{2} l^2 \left\{ \int_s^l \left(\frac{l^2}{x} - x \right)^{\frac{1}{n}} dx - \int_l^1 \left(-\frac{l^2}{x} + x \right)^{\frac{1}{n}} dx \right\} - \frac{1}{2} \int_s^l x^{2-\frac{1}{n}} \left(l^2 - x^2 \right)^{\frac{1}{n}} dx + \frac{1}{2} \int_l^1 x^{2-\frac{1}{n}} \left(-l^2 + x^2 \right)^{\frac{1}{n}} dx \qquad (9)$$

The terms enclosed in brackets in Eqn. 9 are seen to be just Eqn. 5, which is the determining condition for ?, and it clearly vanishes. Thus

$$I = -\frac{1}{2}\int_{s}^{l} x^{2-\frac{1}{n}} \left(l^{2} - x^{2} \right)^{\frac{1}{n}} dx + \frac{1}{2}\int_{l}^{1} x^{2-\frac{1}{n}} \left(-l^{2} + x^{2} \right)^{\frac{1}{n}} dx \qquad (10)$$

By choosing $u = x^{1-\frac{1}{n}}$ and $dv = \left(-l^{2} + x^{2}\right)^{\frac{1}{n}} x \cdot dx$ for the first integral of Eqn. 10,

and choosing $u = x^{1-\frac{1}{n}}$ and $dv = \left(l^{2} - x^{2}\right)^{\frac{1}{n}} x \cdot dx$ for the second integral of Eqn. 10,

and then integrating by parts and combining with Eqn. 7 gives:

$$Q = 2pR^{3} \cdot \left(\frac{R \cdot e^{n-1}}{2K_{ve}} \cdot \frac{dP}{dL} \right)^{\frac{1}{n}} \left\{ \frac{1}{2} \left(\frac{1}{\frac{1}{n}+1} \right) \left[\left(1-l^{2}\right)^{1+\frac{1}{n}} - s^{1-\frac{1}{n}} \left(l^{2} - s^{2} \right)^{1+\frac{1}{n}} - \left(1 - \frac{1}{n} \right) \int_{s}^{1} \left| l^{2} - x^{2} \right|^{1+\frac{1}{n}} x^{-\frac{1}{n}} dx \right] \right\} + p \cdot R^{2} \left(1 - s\right) \cdot V_{slip} \qquad (11)$$

Comparing Eqns. 7 and 11, it can be seen that Eqn. 12 is the results

$$\int_{s}^{1} \left| l^{2} - x^{2} \right|^{1+\frac{1}{n}} x^{-\frac{1}{n}} dx = \left(\frac{1}{\frac{1}{n} + 3} \right) \left[\left(1 - l^{2} \right)^{1+\frac{1}{n}} - s^{1-\frac{1}{n}} \left(l^{2} - s^{2} \right)^{1+\frac{1}{n}} \right] \qquad (12)$$

Which is valid for arbitrary values of “n” for all values of s in the range 0 = s = 1. Thus, an analytical expression for the volume rate-of-flow of a Power-Law fluid through a concentric annulus with equal slip velocities at both the inner and outer boundaries is

$$Q = \frac{np R^{3}}{1+3n} \left(\frac{R \cdot e^{n-1}}{2K_{ve}} \cdot \frac{dP}{dL} \right)^{\frac{1}{n}} \left[\left(1 - l^{2} \right)^{1+\frac{1}{n}} - s^{1-\frac{1}{n}} \left(l^{2} - s^{2} \right)^{1+\frac{1}{n}} \right] + p \cdot R^{2} \left(1 - s \right) \cdot V_{slip} \qquad (13)$$

This is the final equation.

Appendix B Nomenclature

n = Power-Law fluid flow behavior index
P = pressure
R = radius of wellbore
K_{VE} = Volume Equalized Principle consistency index
L = length of flow path
λ = dimensionless radius of maximum velocity in the annulus
? = dimensionless radius
σ = dimensionless outer radius of pipe
ε = specific volume expansion ratio
τ = shear stress
V_{slip} = slip velocity
Q = flow rate

7. DEVELOPMENT OF CUTTINGS MONITORING METHODOLOGY (Task 11)

Investigators: Kaveh Ashenayi and Gerald Kane (Profs Electrical Engr.)

Objectives

The ultimate objective of this task (Task 11) is to develop a non-invasive technique for quantitatively determining the location of cuttings in the annular (drilling) section of the ACTS Flow Loop. There are four different techniques that could be examined. However, as was pointed out in the previous reports, only three have good potential for success. These are Ultrasound, X-Ray/Gamma-Ray and Optical. Of these, we are concentrating on Ultrasonic Sensors that can be used as both transmitters and receivers of sound for Task 11.

Team Composition:

The team responsible for developing instrumentation to measure cuttings concentration and distribution within an annulus consists of Dr. Gerald R. Kane and Dr. Kaveh Ashenayi. Both are registered professional engineers and are professors in the Electrical Engineering Department at the University of Tulsa. MS level graduate students are assisting them. These students have BS degrees in EE and Computer Science. This particular combination works well since successful completion of this project requires skills from both disciplines. To achieve the objectives of this task, we will need to develop a very complicated electronic hardware/sensor and a software package that correctly interprets the ultra-sonic data that is transmitted through a flowing slurry.

Approach

In subtask one of Task 11, a static (followed by a dynamic) radial test cell is to be fabricated and used to develop a preliminary set of instruments to detect the presence of cuttings in this cell. The next step is to proceed to a dynamic case for which cuttings flow as a slurry through an annular geometry.

The main approach to be investigated is the ultrasound transmission. We will further investigate the need for an inner ring by comparing the results of two experiments. First we will setup a set of rings in the outer pipe. We will rotate the angle at which the sound is being transmitted relative to the sand collection. We will measure the sound received and compare it against sound transmitted. After suitable data processing we believe it is possible to get an acceptable picture of what is inside the pipe. This is very similar to the MRI technique used by physicians.

In the second experiment we will repeat the same experiment except we will setup an inner ring of sensors on the inner pipe. The inner ring will act as source and the outer ring will act as receivers. Then we will repeat the experiment above.

Progress to Date

The previous versions of the sensor control board had two different kinds of noise signals that were interfering with the proper operation of the sensors. The first was a high frequency (300 kHz) ground noise that can be and is now filtered out. The second noise signal was at 75 kHz, which is the same frequency as is generated by the sensors when operating in the transmitter mode. This second source of noise was the primary problem.

An independent noise-elimination expert was consulted to arrive at an improved design. The board layout was modified and some parts were replaced. The new board has been assembled and tested. The radiated 75kHz noise is significantly reduced, and the system now functions in an acceptable manner.

Temperature sensitivity tests have been conducted with the new board to assure that the sensor can function at high temperature. The results indicated that the sensor performance does not change significantly up to 190^{o}F

In addition, static gravel tests have been conducted with a plastic outer pipe and an inner steel pipe to evaluate sensor response and performance. The results indicate the system can distinguish between differences in sand concentration. Furthermore, tests indicate that a central ring of sensors mounted on the inner pipe will not be necessary. If a satisfactory measurement system can be achieved with this simplification, it will facilitate installation of the system on the annular section of the ACTS Flow Loop, since the inner pipe will normally rotate.

Additions to the data collection software are proceeding. The software will start by allowing the user to setup the communication characteristics of the system. It then proceeds to identify the number of boards connected. The data received from the sensor board is in the form of ASCII characters. A conversion algorithm has been developed and tested that enables calculation of the numerical voltage value corresponding to the character combinations that are received.

Future Work:

Two sets of experiments will be conducted using a clear plastic cell. First, a set of rings will mounted on the outer pipe. The sound received will be compared with sound transmitted. After suitable data processing, it should be possible to get an acceptable picture of what is inside the pipe.

The second set of experiments will use an inner ring of sensors mounted on the inner pipe. The inner ring will act as a source and the outer ring will act as receivers. The same plastic cell will be used to calibrate the system.

Neural networks will be used to model the effects of flow on the signal received as well as the distribution of gravel inside the cell. This software is needed due to the highly nonlinear nature of the phenomenon of cuttings being transported through an annulus. It has previously been shown by Ozbayoglu, ACTS Task 6, that neural networks can be used to successfully model this type of nonlinear system.

A uniform bed of gravel will be established at the bottom of a horizontal clear plastic pipe. Then a number of measurements will be made. This process will be repeated for different sand volumes. This will produce different heights of sand at the bottom of the pipe. Next, different heights of gravel will be arranged at an angle with respect to the sensors in order to determine how this affects the data. This will conclude the static tests.

Upon successful completion of the static tests, dynamic tests with fluid motion will be conducted. The initial tests will be started with simple movement of a pipe and an annulus to induce fluid motion and see how the readings change. The next step in dynamic testing is to install the system on the Dynamic Test Facility, developed as part of Task 12. Finally, the system will be installed on the ACTS Flow Loop.

Deliverable

A fully operational ultrasonic system installed on the ACTF that is calibrated over a range of slurry flow conditions and can measure variations in cuttings concentration across an annulus and as a function of time.

8. DEVELOPMENT OF A METHOD FOR CHARACTERIZING BUBBLES IN ENERGIZED FLUIDS (TASK 12)

Investigator: Leonard Volk (ACTS Research Associate)

8.1 Introduction

Bubbles (as foam or aerated fluid) will be moving at a high rate (up to 6 ft/sec) in the drilling section of the ACTF, and may be very small (down to 0.01 mm). The bubble size and size distribution influence the fluid rheology and the ability of the fluid to transport cuttings. Bubbles in a shear field (flowing) may tend to be ellipsoidal which might alter both the rheology and transport characteristics.

This project is Task 12 (Develop a Method for Characterizing Bubbles in Energized Fluids in the ACTF During Flow) in the Statement of Work, and is divided into four subtasks:

- Subtask 12.1. Develop/test a microphotographic method for static conditions;
- Subtask 12.2. Develop/test a method for dynamic conditions;
- Subtask 12.3. Develop simple, noninvasive methods for bubble characterization;
- Subtask 12.4. Provide technical assistance for installation on ACTF.

Subtask 12.1 includes (1) magnifying and capturing bubble images, (2) measuring bubble sizes and shapes, and (3) calculating the size distribution and various statistical parameters.

Subtask 12.2 develops the methods needed to apply the results of Subtask 12.1 to rapidly moving fluids, especially the method of "freezing" the motion of the bubbles. A dynamic testing facility will be developed in conjunction with Task 11 for development and verification.

Subtask 12.3, added in year 3, develops simple, inexpensive and "small-in-size" methods for characterizing bubbles. This task was previously referred to as "New Techniques".

Techniques and methods developed under Subtask 12.2 and 3 will be applied to the drilling section of the ACTF in Subtask 12.4.

8.2 Objectives

One of the primary objectives of this task is to develop the methodology and apparatus needed to measure the bubble size, size distribution and shape during cuttings transport experiments.

8.3 Project Status

8.3.2 Dynamic Bubble Characterization

8.3.2.1 Dynamic Imaging

Dynamic Testing Facility (DTF) A Hatachi KP-F120 progressive scan digital camera has been purchased that will be installed on the Nikon microscope attached to the DTF. This camera has a high pixel density (24,100 pixels/mm^2) for high resolution images and high quantum efficiency for improved performance under low light conditions that exist with microscopic imaging. This should significantly improve the image quality.

After several years of frustration searching for software that can recognize bubbles from front illuminated images, we have located a software company that will develop a plug-in for PhotoShop to do the job. So far as we can tell, this capability will be unique to this project. A stop-flow technique is being examined that may allow us to capture bubble images without the need for ultra fast shutter speeds or microsecond flash systems. On those occasions where we want to look at the effect of shear-elongated bubbles, the microsecond flash system will be available. A new objective lens with a longer focal length has been purchased that will allow us to better examine other image–improving techniques, such as polarized light.

Foam Generator/Viscometer A Hatachi KP-F120 has also been purchased for imaging foam bubbles transiting to the viscometer. Also part of this system will be a x10 magnification lens system. There is also considerable magnification provided by the digital camera-computer interface so that the total magnification of around x250 should be sufficient to image bubbles. As with the DTF, we are also looking into a stop-flow technique for capturing bubble images.

ACTF A Hatachi KP-F120 digital camera has been purchased along with a SMZ-800 Nikon stereomicroscope for capturing bubble images of foam generated on the ACTF. As with the DTF and Foam Generator/Viscometer, a stop-flow technique is under investigation.

8.3.2.2 Dynamic Testing Facility

A design modification to the DTF has been completed that will offer several advantages:

- Reduction in foam generation time, maybe by as much as 80%
- Much easier directions for foam generation
- Reduced dead volume that will decrease the foam stabilization time
- Direct measurement of the volumetric flow through the Haake rheometer now attached to the DTF
- Verification of stop-flow imaging technique
- Simplified and improved bubble image capturing
- Reduced friction loss (added shear) of foam flowing through the Haake rheometer

These modifications will be installed during the next quarter.

8.3.3 Novel Techniques for Bubble Characterization

Design of an improved electronic package for the photo diode is underway. This new design should provide much better signal gain and linearity.

8.4 Planned Activities

8.4.2 Dynamic Bubble Characterization

- Work with software vendor developing bubble imaging plug-in
- Install new digital camera on DTF.
- Develop stop-flow technique

8.4.3 Novel Techniques for Bubble Characterization

- Determine optimum method of maintaining clean optical windows
- Modify average bubble size device for ease of removal
- Improve electronics for average bubble size determination
- Calibrate the average bubble size prototype
- Complete construction for the foam quality prototype and calibrate.

9. SAFETY PROGRAM (TASK 1S)

Chairman, Process Hazards Review Team: Leonard Volk (ACTS R.A.)

9.1 Introduction

This project was initiated during the fourth quarter of 2000 to assess the hazards associated with the Advanced Cuttings Transport Facility (ACTF) and develop an Action Plan to address problems discovered during this Hazards Review. A Hazards Review is an industry accepted method used to improve the overall safety characteristics and reduce the possibilities of accidents in the work place. Each individual component of the ACTF is examined as to the effect and consequences on safety, health, and the environment, of the component in all possible operational modes. A Hazards Review can result in equipment modification, inspection and testing, documentation, personal protective equipment, personnel training, and/or emergency training.

The Hazards Review process begins by selecting a review method. Next a team of qualified individuals must be formed. This team should include those knowledgeable in the review process and those familiar with the process to be reviewed. Prior to beginning the review, all available documentation needs to be gathered. This includes schematics, organized training, periodic inspections and testing results, design and construction documents, operating procedures, etc. Once the schematics have been verified and the operator of the equipment or process has reviewed its operation with the team, the Hazards Review begins.

The review should continue uninterrupted until completed. After the findings and recommendations have been completed, a draft report is issued and reviewed by all team members, and the operator of the process or equipment. Following this review, any changes are incorporated and a final report issued. This completes the Hazard Review process. The operator then needs to develop an action plan to implement the recommendations from the Hazard Review. In our case, team members will participate in developing this plan.

9.2 Objective

The first objective of this task is to identify problems (findings) that might result in injury, property damage or the release of environmentally damaging materials and provide recommendations to minimize them, and to develop an action plan based on these recommendations.

A second objective is to establish standards for when a hazards review for the ACTS Flow Loop should be repeated.

A third objective is to develop a safety training course for all personnel that are involved in using the ACTS Flow Loop and equipment.

9.3 Project Status

Table 9.1 gives the status of the Findings from the first Hazards Review. The first column lists the Finding and the next one gives the occurrences of this Finding as listed in the "What If" table in the Hazards Review report. The next column categorizes the Finding as to safety (S), environmental (E), or operational (O). The next column identifies the relative risk of occurrence of the event identified by this Finding, assuming no safeguards are in place (1 = lowest risk; 3 = highest risk). The fifth column gives the severity of the consequence if this event occurs (1 = lowest severity; 3 = highest severity). The column labeled "Status" indicates the % completion of the Finding. The last column lists the lead individual addressing the Finding (MP – Mark Pickell, ST – Steve Turpin, LV – Len Volk). This table differs somewhat from the one presented in the last quarterly report. Columns have been added for the relative risk and severity of an occurrence.

Once the Findings in Action Plan #1 have been addressed, a second Hazards Review will begin to examine all new additions to the ACTF.

Table 9.2 lists the classes or training, The University of Tulsa course number, how frequently training is required, who needs the training and whether or not specific training is needed for those working on the ACTS. Notice that there are four general activity locations for the ACTS: the ACTF, mud lab, rheology room and the Dynamic Testing Facility. Faculty here refers to anyone working on the project that is not a student. Maintenance personnel refer to faculty or staff that perform maintenance on the ACTF. The column labeled ACTS Specific refers to training that specifically applies to the ACTS. Table 9.3 provides a very brief description of these courses.

TABLE 9.1

STATUS OF HAZARDS REVIEW FINDINGS AS OF 4-22-03

FINDING	OCCURRENCE	TYPE	RISK	CONSEQ	STATUS	LEAD
No monitoring of "no flow" condition of pump while operating	1, 2, 3, 8, 9, 12, 15, 31, 37, 41, 98, 118, 119	O	1	2	20	ST
No design documentation for piping or fittings	7, 23, 24, 29	S			20	LV
No design documentation for relief valves	32, 96, 102	S			20	LV
No inspection documentation for relief valves	33, 97, 103	S			20	LV
Insufficient splash protection	39, 40, 48, 49, 110, 111	S	2	2	100	MP
Improper hose for application	42	S	2	2	100	MP
No design documentation for hose	43, 46, 55, 65, 121, 127	S			10	LV
No inspection procedure & documentation for hoses	44, 47, 56, 66, 122, 128	S	2	2	10	LV

Incorrect relief valve pressure setting	45, 95, 101	S	2	3	40	MP
No pressure bleed valve	58	S	1	2	100	ST
Air hose not secured	59	S	1	3	100	MP
No reverse flow protection	60	O	1	2	10	ST
No relief protection	61	S	1	3	10	ST
Incomplete design documentation of components (valves, etc.)	67	S			90	LV
No written operating procedure	74, 76, 82, 84, 86, 88, 89, 91, 107, 109	S	3	3	0	MP
Improper direction of released fluid	85, 92	S	1	2	50	ST
Inadequate protection against high-volume gas release	113, 115	S	2	3	10	MP
Flammable material too close to ignition source	123	S	1	3	10	MP
No secondary spill containment	124	E	1	2	10	ST
No placarding or labeling of containers or equipment storing flammable or hazardous material	125, 134	S	1	2	50	MP
Tubing incompatible with contents	126	E	2	2	100	ST
No protection against mechanical breakage – diesel site tube	129	E	1	2	10	ST
No automatic shut-off of fuel supply	130	S	1	3	10	ST
Inadequate number/location of fire extinguishers	131	S	1	3	10	MP
No site-specific emergency action plan	132	S	1	3	10	LV
No specific lock-out, tag-out procedure	133	S	1	3	10	LV
No corrosion inspection procedure & documentation for corrosion	135	S	1	3	10	LV
No written operating procedure	137	S	2	3	0	MP
No documented training procedure for operating personnel	138	S	2	3	0	MP
No documented safety training program	139, 145-147	S	2	3	10	LV

No protecting barrier around facility	140	S	1	2	0	ST
No hazard communication training	141	S	1	3	20	LV
No training or documentation on cleaning up small spills	142	S	1	1	10	LV
No MSD sheets available on site	143	S	1	3	20	LV

TABLE 9.2.

ACTS Training for the ACTF, Mud Lab, DTF and Rheometer Room

CLASS	TU #	FREQUENCY	FACULTY	STUDENTS	MAINTENANCE	ACTS SPECIFIC
Bloodborne Pathogens	12	Initial & Annual	Yes	Yes		No
Emergency Action Plan	1	Initial	Yes	Yes		Yes. Severe weather, fire, explosion, spills, etc.
Fall Protection	23	Initial	No	No	Yes	No
Forklift Safety	18	Initial & every 3 yr	No*	No*	Yes**	No
Hazard Communication - Lab	14	Initial & every 2 yr	Yes	Yes		Specific chemicals, hazards, MSDS locations
Hazard Communication – Non-Lab	13	Initial & Annual	Yes	Yes		Specific chemicals, hazards, MSDS locations
Personal Protective Equipment	20	Initial	Yes	Yes		Discuss specific hazards
Lock-Out/Tag-Out (Authorized)	15	Initial	No	No	Yes	No
Lock-Out/Tag-Out (Affected)	16	Initial	Yes	Yes		No
Permit Required – Confined Space			No	No	No	Discuss no entry allowed in storage tanks
Spill Control & Containment	4	Initial & Annual	No	No	Yes	Discuss responsibility of students, faculty for small & large spills

***** Unless the individual uses a forklift

****** If individual uses a forklift

TABLE 9.3.
Course Descriptions

COURSE	DESCRIPTION
Blood born Pathogens	Discusses the diseases that can be transmitted by contact with body fluids due to rendering of first aid or other activities in the work place
Emergency Action Plan	Covers actions employees/students must take in the event of an emergency such as fire, tornado, etc. Covers the use of portable fire extinguishers and the ways to prevent fires in the work
Fall Protection	Covers the safe use of ladders and fall protection
Forklift Safety	Discusses the safety considerations to be observed when operating a forklift, how to read capacity charts and how to perform operator pre-operation checks and maintenance
Hazard Communication - Lab	Includes the health and safety information concerning the proper use and possible deleterious effects of substances (chemicals) in the work area. Discusses use of MSDS. This course is designed for those working in a laboratory environment.
Hazard Communication – Non-Lab	Same as above but for those whose work place is other than a chemical laboratory
Personal Protective Equipment	Covers the effects of noise in the work area and how to minimize it. Also addresses proper selection, use and care of items such as gloves, face shields, hearing protectors, safety glasses, aprons, coveralls, etc.
Lock-Out/Tag-Out (Authorized)	This course is designed for those authorized to lock or tag equipment as out of service, usually for repair.
Lock-Out/Tag-Out (Affected)	This covers the precautions workers must observe when equipment is tagged or locked out of service.
Spill Control & Containment	This course presents the general procedures for cleaning up chemical spills

9.4 Planned Activities

- Complete addressing the Findings listed in Action Plan #
- Begin Hazards Review of new modifications to the ACTF

10. TECHNOLOGY TRANSFER

Meetings with Petroleum and Service Companies

Representatives from the following JIP members attended the May 20, 2003 Advisory Board Meeting (ABM): the U.S. DOE, British Petroleum, Baker-Hughes, ChevronTexaco, Schlumberger, Halliburton, Statoil, Total and Weatherford International. There were also visitors from the following companies: ExxonMobil, Anadarko Petroleum, Saudi Aramco, Environmental Drilling Technology, and Temco (builder of the new Foam Generator).

A representative from ConocoPhillips did not attend the May ABM. However, a drilling manager did visit our facilities later during the month of June. His responses and reactions were favorable, and he has asked for a Letter of Agreement to join TUDRP, but will probably not join the ACTS Project during the final year of the current 5-Year project. This is especially welcome news since they are now the third largest petroleum company in the US.

ACTS-JIP Advisory Board Meeting

The next Advisory Board Meeting will held on November 18, 2003. In addition to the DOE, there are currently 10 member companies participating in the ACTS-JIP Project. They are: 1) British Petroleum, 2) Baker-Hughes , 3) ChevronTexaco, 4) Schlumberger Dowell, 5) Halliburton, 6) Intevep, 7) Petrobras, 8) Statoil, 9) TotalFina-Elf, and
10) Weatherford International.