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ABSTRACT

ACTS flow loop is now operational under elevated pressure and temperature. Currently, experiments with water under pressure and temperature are being conducted.

Based on the analysis of Fann 70 data, empirical correlations defining the shear stress as a function of temperature, pressure and the shear rate have been developed for Petrobras synthetic drilling fluids. PVT equipment has been modified for testing Synthetic drilling fluids. Initial calibration tests have been conducted by using water. Currently, the base oil of the Petrobras synthetic drilling fluid is being tested.

Foam flow experiments have been conducted. Currently, more experiments are being conducted while data are being analyzed to characterize the rheology of the foam.

Cuttings transport experiments have been conducted using air, water and cuttings. Preliminary results have shown that it may not be possible to avoid cuttings bed depositon under any practical combination of air and water flow rates.

Foam stability analyses have been conducted. Effects of salt and oil concentration on the foam stability have been investigated.

A software for controlling the data sampling and data storage during cuttings monitoring process have been developed.

TABLE OF CONTENTS

DISCLAIMER	2
ABSTRACT	3
TABLE OF CONTENTS	4
LIST OF TABLES	5
LIST OF FIGURES	6
1. INTRODUCTION	8
2. EXECUTIVE SUMMARY	9
3. ACTF DESIGN AND CONSTRUCTION ACCOMPLISHMENTS	10
4. STUDY OF FLOW OF SYNTHETIC DRILLING FLUIDS UNDER ELEVATED PRESSURE AND TEMPERATURE CONDITIONS.	14
5. STUDY OF CUTTINGS TRANSPORT WITH FOAM UNDER LPAT CONDITION	34
6. STUDY OF CUTTINGS TRANSPORT WITH AERATED MUDS UNDER LPAT CONDITIONS	38
7. STUDY OF FOAM FLOW BEHAVIOR UNDER EPET CONDITIONS.	50
8. DEVELOPMENT OF CUTTINGS MONITORING METHODOLOGY	61
9. DEVELOPMENT OF A METHOD FOR CHARACTERIZING BUBBLES IN ENERGIZED FLUIDS	63
10. TECHNOLOGY TRANSFER	66

LIST OF TABLES

STUDY OF FLOW OF SYNTHETIC DRILLING FLUIDS UNDER ELEVATED PRESSURE AND TEMPERATURE CONDITIONS

Table 4.1 Coefficient Analysis of RDR vs. Temperature for Arrhenius Relation	21
Table 4.2 Modeling of Coefficient 'C ₁ ' with respect to Pressure	22
Table 4.3 Modeling of Coefficient 'C ₂ ' with respect to Pressure	22
Table 4.4 Test Matrix for Experimental Study of Synthetic Based Oil and Drilling Fluids with PVT Apparatus	29
Table A-1 Correlation Between Coefficient 'C3' and Shear Rate	30
Table A-2 Correlation Between Coefficient 'C4' and Shear Rate	30
Table A-3 Correlation Between Coefficient 'C5' and Shear Rate	31
Table A-4 Correlation Between Coefficient 'C6' and Shear Rate	31
Table A-5 Correlation Between Coefficient 'C7' and Shear Rate	32
Table A-6 Correlation Between Coefficient 'C8' and Shear Rate	32
Table A-7 Correlation Between Coefficient 'C9' and Shear Rate	32
Table A-8 Correlation Between Coefficient 'C10' and Shear Rate	33

STUDY OF CUTTINGS TRANSPORT WITH AERATED MUDS UNDER LPAT CONDITIONS

Table 6.1 Modified Test Matrix	42
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STUDY OF FOAM FLOW BEHAVIOR UNDER ELEVATED PRESSURE AND ELEVATED TEMPERATURE CONDITIONS

Table 7.1 Test Matrix	52
Table 7.2 PVT Test Data of Foam	54

LIST OF FIGURES

ACTF DESIGN AND CONSTRUCTION ACCOMPLISHMENTS

Figure 3.1 Heat Exchanger and Boiler	10
Figure 3.2 Chiller	11
Figure 3.3 Mud Tanks	11
Figure 3.4 ACTS Flow Loop-Insulated	12
Figure 3.5 Schematic Drawing of the Current Flow Loop Configuration.	13

STUDY OF FLOW OF SYNTHETIC DRILLING FLUIDS UNDER ELEVATED PRESSURE AND TEMPERATURE CONDITIONS

Figure 4.1 Effect of Temperature on Synthetic Based Drilling Fluid RDR Readings @ Different Shear Rates (Pressure = 500 psig)	18
Figure 4.2 Effect of Temperature on Synthetic Based Drilling Fluid RDR Readings @ Different Shear Rates (Pressure = 2000 psig)	18
Figure 4.3 Effect of Temperature on Synthetic Based Drilling Fluid RDR Readings @ Different Shear Rates (Pressure = 4000 psig)	19
Figure 4.4 Effect of Temperature on Synthetic Based Drilling Fluid RDR Readings @ Different Shear Rates (Pressure = 8000 psig)	19
Figure 4.5 Effect of Temperature on Synthetic Based Drilling Fluid RDR Readings @ Different Shear Rates (Pressure = 12000 psig)	20
Figure 4.6 Comparison of Experimental and Calculated Dial readings for Various Temperatures @ 500 psi and 600 rpm	23
Figure 4.7 Comparison of Experimental and Calculated Dial readings for Various Temperatures @ 2000 psi and 300 rpm	23
Figure 4.8 Comparison of Experimental and Calculated Dial readings for Various Temperatures @ 8000 psi and 6 rpm	24
Figure 4.9 Schematic View of PVT Cell and Sampling Lines	26
Figure 4.10 Comparison of Measured and Published Water Densities at Various Pressures and 70 °F	27
Figure 4.11 Comparison of Measured and Published Water Densities at Various Pressures and 120 °F	28
Figure 4.12 Comparison of Measured and Published Water Densities at Various Pressures and 200 °F	28

STUDY OF CUTTINGS TRANSPORT WITH FOAM UNDER LOW PRESSURE AND AMBIENT TEMPERATURE CONDITIONS

Figure 5.1 Schematic Drawing of the Additional Mixing Assembly	35
Figure 5.2 Experimental data for 2 inch pipe	36
Figure 5.3 Experimental data for 3 inch pipe	36
Figure 5.4 Experimental data for 4 inch pipe	37
Figure 5.5 Experimental data for 8 inch-4.5 inch annulus	37

STUDY OF CUTTINGS TRANSPORT WITH AERATED MUDS UNDER LOW PRESSURE AND AMBIENT TEMPERATURE CONDITIONS

Figure 6.1 Accumulation of Cuttings in the Test Section for a Total Flow Rate of 200 GPM	42
Figure 6.2 Bed Height vs. Gas Volumetric Fraction for a Total Flow Rate of 200 GPM	43
Figure 6.3 Variation of Frictional Pressure Drop for a Total Flow Rate of 200 GPM	43
Figure 6.4 Accumulation of Cuttings in the Test Section for a Total Flow Rate of 300 GPM.	44
Figure 6.5 Bed Height vs. Gas Volumetric Fraction for a Total Flow Rate of 300 GPM	44
Figure 6.6 Variation of Frictional Pressure Drop for a Total Flow Rate of 300 GPM	45
Figure 6.7 Accumulation of Cuttings in the Test Section for a Total Flow Rate of 400 GPM.	46
Figure 6.8 Bed Height vs. Gas Volumetric Fraction for a Total Flow Rate of 400 GPM	46
Figure 6.9 Variation of Frictional Pressure Drop for a Total Flow Rate of 400 GPM	46
Figure 6.10 Accumulation of Cuttings in the Test Section for a Total Flow Rate of 500 GPM-only liquid	47
Figure 6.11 Accumulation of Cuttings in the Test Section for a Total Flow Rate of 500 GPM.	47
Figure 6.12 Bed Height vs. Gas Volumetric Fraction for a Total Flow Rate of 500 GPM	48
Figure 6.13 Variation of Frictional Pressure Drop for a Total Flow Rate of 500 GPM	48

STUDY OF FOAM FLOW BEHAVIOR UNDER ELEVATED PRESSURE AND ELEVATED TEMPERATURE CONDITIONS

Figure 7.1 Drained Liquid Volume – foamer Solution 1% v/v (with no salt or oil)	57
Figure 7.2 Drained Liquid Volume-Salt Concentration Effect	58
Figure 7.3 Drainage Rate and Half Life Time of Foam with Salt)	58
Figure 7.4 Foamability as a Function of Salt	59
Figure 7.5 Drainage Rate and Half Life Time of Foam with Mineral Oil)	59
Figure 7.6 Schematic Drawing of PVT Cell	60

DEVELOPMENT OF A METHOD FOR CHARACTERIZING BUBBLES IN ENERGIZED FLUIDS

Figure 9.1 Methods of Sample Illustration	65
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1. INTRODUCTION

This third quarterly report includes a review of the progress made in ACTS Flow Loop development and research during the period of time between January 15, 2000 and April 15, 2000.

The report presents information on the following specific subjects;

- a-) Progress in Advanced Cuttings Transport Facility design and development,
- b-) Progress report on the research project "Study of Flow of Synthetic Drilling Fluids Under Elevated Pressure and Temperature Conditions",
- c-) Progress report on the research project " Study of Cuttings Transport with Foam Under LPAT Conditions (Joint Project with TUDRP)",
- d-) Progress report on the research project " Study of Cuttings Transport with Aerated Muds Under LPAT Conditions (Joint Project with TUDRP)",
- e-) Progress report on the research project " Study of Foam Flow Behavior Under EPET Conditions",
- f-) Progress report on the instrumentation tasks (Tasks 11 and 12)
- g-) Activities towards technology transfer and developing contacts with oil and service company members.

2. EXECUTIVE SUMMARY

The Year 2 construction plans are well in progress. All the essential parts of the heating/cooling system (Task # 1, Year 1) (i.e. heat exchanger, boiler and cooling tower) have been received and installed in the flow loop. The ACTS flow loop is now operational under elevated pressure and temperature. Currently water flow tests under elevated pressure and temperature are being conducted.

Analysis of Fann 70 data has been completed. Empirical correlations of shear stress as a function of temperature, pressure and shear rate for Petrobras data have been developed. PVT (Pressure volume temperature) equipment has been modified for testing synthetic drilling fluids. The equipment was calibrated by measuring PVT properties of water. Currently, the base oil of the synthetic drilling fluid is being tested.

Experiments with foam flow in pipes and annulus have been conducted. Analysis of data for rheological characterization of foam is in progress.

Cuttings transport experiments have been conducted for by using air, water and solid mixtures. Preliminary results have shown that it may not be possible to avoid cuttings bed deposition under any practical combination of air and water flow rates. Results have also shown that for the given borehole geometry and the total flow rate, the cuttings bed height in horizontal wells is increased by increasing gas flow rate. A reduction in the average pressure drop was also observed as the gas flow rate is increased.

Design concepts for ACTS flow-loop modification for aerated mud and foam flow (Task #2, Year II) have been discussed with members of ACTS-JIP. Some possible modification of the initial design concepts have been identified based on the discussion with industry members.

Experiments have been conducted to investigate the influence of salt and mineral oil addition on the foam stability. The foam stability was measured by using two different parameters: half life time and drainage rate. Results indicate that stability is not considerably affected by the salt presence up to 20% w/v. The oil presence, however, enhanced the foam stability.

A software for controlling the data sampling and data storage during cuttings monitoring process have been developed.

Petrobras joined the ACTS-JIP. Unocal, however, announced that they will not be able to join ACTS-JIP due to re-organization of the company and consequent reduction in their R&D budget.

3. ACTF DESIGN AND CONSTRUCTION ACCOMPLISHMENTS

A number of new components ordered previously have been received, installed, and made operational during this quarter. Most significant of these are the heat exchanger and boiler(Fig. 3.1), the chiller (Fig. 3.2), 100 bbl. mud tank (Fig. 3.3), piping and insulation(Fig. 3.4).

Piping has been configured to allow the pump to take suction from either of the mud tanks or suction from one tank and discharge to the other by opening or closing valves. The new tank, the previously existing tank, and the test loop piping have been fully insulated to minimize heat loss during high temperature experiments.

The ACTS flow loop is now operational under elevated pressure and temperature. Currently, water flow experiments are being conducted under elevated pressure and temperature.

Figure 3.5 shows a floor plan of the current ACTS test loop with recent additions. Some future additions are also indicated in dashed lines.

Figure 3.1 Heat Exchanger and Boiler

Figure 3.2 Chiller

Figure 3.3 Mud Tanks

Figure 3.4 ACTS Flow Loop-Insulated

Figure 3.5 Schematic Drawing of the Current Flow Loop Configuration

4. STUDY OF FLOW OF SYNTHETIC DRILLING FLUIDS UNDER ELEVATED PRESSURE AND TEMPERATURE CONDITIONS

Investigator: Barkim Demirdal

4.1 Objectives

- Determine the effect of temperature and pressure on rheological parameters of synthetic based drilling fluid using both rotational viscometer and pipe viscometer
- Determine the relation between wall parameters (n' and K') and rheological parameters (n , K and t_y) using the experimental data and analytical relations
- Determine the change in wall parameters with change in flow regime and geometry and modify wall parameters as a function of down hole conditions, geometry and flow regime
- Compare the pressure losses determined using rheological parameters obtained from rotational viscometers with the pressure losses obtained using pipe viscometer
- Determine the effect of annular flow on the wall parameter of synthetic based drilling fluids. To investigate the effect of pressure and temperature on equivalent diameter
- Compare the effect of temperature and pressure on the densities of base oil and synthetic based drilling fluid and determine whether, additives in the mud has major influences on density changes with temperature and pressure
- Compare the experimental results obtained under laminar flow with analytical solutions determined for Yield Power Law fluids and modify the analytical solutions with introducing the effect of pressure and temperature to rheological parameters and density
- To compare the experimental results obtained under transient and turbulent conditions with empirical correlations and modify these equations with temperature and pressure corrections in density and rheological parameters

4.2 Project Status

Rheological analysis of Petrobras Synthetic Drilling Fluids using Fann 70 rheometer has been completed. Some preliminary results were presented in the second quarterly report. Presented in this report are an approach followed for the analysis of the Fann 70 data and the resultant empirical correlations showing the effect of temperature, pressure and the shear rate on the rheology of Petrobras synthetic drilling fluid.

Modification of a conventional Pressure Volume Temperature (PVT) cell for Synthetic Drilling Fluid Testing has been completed. Initial calibration tests with

water have been conducted. PVT analysis of Petrobras Synthetic drilling fluid is in progress.

4.2.1 Rheological Characterization of Petrobras Synthetic Based Drilling Fluid

Using constant rheological models like Bingham Plastic, Power law or Yield Power Law may not show the exact behavior of the fluid for a large range of shear rate-shear stress data (especially at various pressure-temperature conditions). Therefore, in this study, it has been decided to use raw shear stress data (Determined using Fann 70 Rotational Viscometer) for rheological characterization purposes.

It was decided to use Hemphill's "Relative Dial Readings (RDR)" approach [Hemphill, T.; SPE 35330, March, 1996] for rheological characterization that is independent of any rheological model. RDRs are defined as the ratio of dial readings determined for specific pressure and temperatures (using Fann 70 Rotational Viscometer) to dial readings determined under surface conditions (14.7 psi and 70 °F)

$$RDR = \frac{q_{T,P}}{q_{14.7\text{ psi}, 70^\circ F}} \dots\dots\dots(1)$$

It was aimed to find out a single relation that will relate RDRs with shear rate, temperature and pressure. Once this relation is known, then fluids' shear stress could be determined under any down hole conditions at any flow rate. In order to determine such a function, non-linear and linear regression analysis techniques were used. Most of the non-linear regression analysis had been conducted using a statistical analysis software package called "Statistica".

Procedure to Develop the Model:

1. Fann 70 test data were plotted to determine the effect of temperature and pressure on RDRs at each shear rate (Figures 4.1-4.5). It has been found out that the effect of temperature on RDRs is more dominant than the effect of pressure. Analysis of the test data also showed that pressure is more effective at lower temperatures and higher shear rates. However, the pressure effect diminishes especially at high temperatures regardless of the shear rate applied to the fluid system. Another interesting property of the fluid is that, dial readings (i.e. shear stress) of the fluid are increasing with increasing temperature above 200°F, especially at lower shear rates (i.e. temperature gelation effect). For this reason, the effect of temperature on RDR is determined at each pressure- shear rate condition at the starting point of the rheological characterization. It has been found out that at all pressure and shear rates, there is an inverse relation between RDR and temperature. However, it was also seen that at high temperatures gel effect increases with increasing pressure as well.

2. "Arrhenius' Relation" was used to approximate the relation between RDR and temperature with high accuracy.

$$RDR(T) = C_1 \exp(C_2 / T) \dots\dots\dots(2)$$

3. Once the relation between RDR and temperature is known, the next step is to relate correlation coefficients of the model to pressure and shear rate. It was found that, both C_1 and C_2 are functions of pressure and shear rate (Table-4.1). Consequently, RDR as a function of temperature, pressure and shear rate can be shown as follows;

$$RDR(T, P, g) = C_1(P, g) \exp[(C_2(P, g) / T)] \dots\dots\dots(3)$$

In order to get a general expression, regression analysis methods should be used to determine the effect of pressure and shear rate on those constants. It has been decided to determine the effect of pressure on C_1 and C_2 under constant shear rate conditions as the second part of rheological characterization process.

A third degree polynomial defines the relation between C_1 and pressure as follows;

$$C_1(P) = C_3 + C_4 * P - C_5 * P^2 + C_6 * P^3 \dots\dots\dots(4)$$

The absolute error range of this relation in approximating C_1 , ranges from 0.2-12 %. The highest errors (10-12 %) occurred while determining the C_1 at pressure of 2000 psig. Other than these, they are always smaller than 10 % (Table-4.2).

Similar analysis has been carried on to determine the effect of pressure on C_2 . It has been found that, again a third degree polynomial best describes the effect of pressure on coefficient C_2 under constant shear rate conditions.

$$C_2(P) = C_7 - C_8 * P + C_9 * P^2 - C_{10} * P^3 \dots\dots\dots(5)$$

The absolute error of the above relation in determining coefficient C_2 is ranging between 0.06-12.5 %. Again the highest errors found to take place while determining the relation between coefficient and 2000 psig (Table 4.3).

6. In order to determine $C_1(P, g)$ and $C_2(P, g)$ to use in equation (3), the effect of shear rate on coefficients shown in equation (4) and (5) should be determined. Non-linear regression analysis has been carried out using either one parameter or two parameter curves. The relations between coefficients and shear rates are shown in the Appendix-A.

7. Substituting correlations defined in Appendix (1a-4a) into equation (4), coefficient C_1 can be written as a function of pressure and shear rate as follows;

$$C_1(P, g) = (0.0371 \ln(g) + 0.0039) + [4.289 \times 10^{-5} * \log 10(g) - 3.476 \times 10^{-6}] * P - [-5.926 \times 10^{-10} + 8.499 \times 10^{-9} * \log 10(g)] * P^2 + [-6.636 \times 10^{-14} + 4.436 \times 10^{-13} * \log 10(g)] * P^3 \dots (6)$$

Similarly, substituting relations (5a-8a) in to equation (5), coefficient C_2 can be written as a function of pressure and shear rate as follows;

$$C_2(P, g) = [177.307 * (1 + g)^{(-0.1009353)}] - 0.025 * P + [-5.674 \times 10^{-6} + 7.083 \times 10^{-7} * \log 10(g)] * P^2 - [2.284 \times 10^{-10} + 6.616 \times 10^{-11} * \log 10(g)] * P^3 \dots (7)$$

8. These two equations (6 and 7) can be substituted into equation (3) and equation relating RDR to both down hole conditions (pressure and temperature) and shear rate (in other words flow rate or velocity) can be determined by using one equation with the form;

$$RDR(T, P, g) = \frac{q_{P,T}}{q_{14.7 \text{ psi}, 70^\circ F}} = C_1(P, g) \exp[(C_2(P, g)/T)] \dots (8)$$

Finally, knowing the surface readings of a particular fluid, shear stresses of the fluid at any downhole conditions under any flow rate can be determined by using this one unique relation.

As a next step, the applicability of the proposed model had tested. Dial readings determined using equation (8) were compared with dial readings of Fann 70 rotational viscometer for each pressure, temperature and shear rate cases.

Figure 4.1 -Effect of Temperature on Synthetic Based Drilling Fluid RDR Readings @ Different Shear Rates (Pressure = 500 psig)

Figure 4.2 - Effect of Temperature on Synthetic Based Drilling Fluid RDR Readings @ Different Shear Rates (Pressure = 2000 psig)

Figure 4.3 - Effect of Temperature on Synthetic Based Drilling Fluid RDR Readings @ Different Shear Rates (Pressure = 4000 psig)

Figure 4.4 - Effect of Temperature on Synthetic Based Drilling Fluid RDR Readings @ Different Shear Rates (Pressure = 8000 psig).

Figure 4.5 - Effect of Temperature on Synthetic Based Drilling Fluid RDR Readings @ Different Shear Rates (Pressure = 12,000 psig)

TABLE 4.1-Coefficient Analysis of RDR vs. Temperature for Arrhenius Relation

Pressure	Shear Rate	R^2	C1	C2
<i>psi</i>	Rpm			
500	600	0.98386561	0.320826	80.6122
	300	0.988214928	0.272093	85.2653
	200	0.987698069	0.250496	87.6856
	100	0.994886554	0.225315	92.8595
	6	0.998440608	0.080229	128.702
	3	0.998060941	0.056531	145.082
2000	600	0.986267472	0.352176	81.9132
	300	0.987618564	0.304635	85.3109
	200	0.988771697	0.281941	86.292
	100	0.99640324	0.254262	89.6297
	6	0.995325476	0.091201	123.519
	3	0.99398906	0.083536	129.377
4000	600	0.95942025	0.458345	78.0105
	300	0.965974466	0.391593	82.0268
	200	0.966190703	0.35925	83.2525
	100	0.981506304	0.32246	84.9091
	6	0.997921082	0.082948	125.097
	3	0.997921082	0.093316	125.097
8000	600	0.996443168	0.298135	164.262
	300	0.996523028	0.241878	169.561
	200	0.99920016	0.22308	169.003
	100	0.997921082	0.185524	172.998
	6	0.90181613	0.053721	199.601
	3	0.90181613	0.060436	199.601
12000	600	0.990641996	0.361526	171.845
	300	0.995265617	0.285691	180.328
	200	0.995944121	0.254668	180.683
	100	0.999540053	0.193276	188.972
	6	0.991259184	0.04809	246.669
	3	0.991259184	0.030311	268.491

Table 4.2- Modeling of Coefficient 'C₁' with respect to Pressure

Press	C1 (3 RPM)	C1 (3cal)	Error, %	C1 (6RPM)	C1(6cal)	Error, %
500	0.056531	0.056797675	0.47	0.080229	0.0806435	0.51
2000	0.083536	0.0840232	0.58	0.091201	0.08882	2.07
4000	0.093316	0.0935216	0.22	0.082948	0.084168	1.47
8000	0.060436	0.0608368	0.66	0.053721	0.052856	1.61
12000	0.030311	0.0307312	1.38	0.04809	0.04788	0.43
Press	C1 (100 RPM)	C1 (100cal)	Error, %	C1 (200 RPM)	C1 (200cal)	Error, %
500	0.225315	0.213327938	5.32	0.250496	0.237549825	5.16
2000	0.254262	0.285288	12.20	0.281941	0.3161088	12.11
4000	0.32246	0.298024	7.57	0.35925	0.3325904	7.42
8000	0.185524	0.193632	4.37	0.22308	0.2318832	3.94
12000	0.193276	0.192408	0.44	0.254668	0.2533008	0.53

Press	C1 (300 RPM)	C1 (300cal)	Error, %	C1 (600 RPM)	C1 (600cal)	Error, %
500	0.272093	0.25676075	5.63	0.320826	0.3028365	5.60
2000	0.304635	0.342848	12.54	0.352176	0.399096	13.3
4000	0.391593	0.360464	7.94	0.458345	0.421448	8.05
8000	0.241878	0.250832	3.70	0.298135	0.310104	4.01
12000	0.285691	0.282768	1.02	0.361526	0.359336	0.60

Table4.3- Modeling of Coefficient 'C₂' with respect to Pressure

Press	C2 (3 RPM)	C2 (3cal)	Error, %	C2 (6RPM)	C2 (6cal)	Error, %
500	145.0821	146.6956125	1.11	128.7026	130.7346625	1.57
2000	129.3772	124.8162	3.52	123.5191	118.2454	4.26
4000	125.0977	127.8986	2.23	125.0977	129.0502	3.15
8000	199.6012	197.2938	1.15	199.6012	197.8726	0.86
12000	268.4918	266.8042	0.62	246.6694	246.2214	0.18
Press	C2 (100 RPM)	C2 (100cal)	Error, %	C2 (200 RPM)	C2 (200cal)	Error, %
500	92.85959	96.5737875	3.99	87.6856	91.650125	4.52
2000	89.6297	78.8544	12.02	86.292	77.27	10.45
4000	84.9091	91.1032	7.29	83.2525	92.134	10.66
8000	172.9984	167.0136	3.45	169.0032	168.902	0.05
12000	188.9726	184.2104	2.52	180.6837	184.55	2.13
Press	C2 (300 RPM)	C2 (300cal)	Error, %	C2 (600 RPM)	C2 (600cal)	Error, %
500	85.26536	89.2961625	4.72	80.61222	84.9181625	5.34
2000	85.3109	74.9994	12.08	81.9132	71.6354	12.54
4000	82.0268	90.0162	9.73	78.0105	87.2202	11.80
8000	169.5616	166.5666	1.76	164.2622	162.9386	0.80
12000	180.3289	180.1154	0.11	171.8458	174.3114	1.43

Comparison of Calculated and Measured Dial Reading Results:

Dial reading results obtained using Fann 70 rotational viscometer were compared to dial readings calculated with the proposed model (Figures 4.6- 4.8). It was seen that the agreement between the model and experimental results was not always good. To determine the weak points of the model, a sensitivity analysis was carried out.

Figure 4.6 - Comparison of Experimental and Calculated Dial Readings for various Temperatures @ 500 psi and 600 rpm

Figure 4-7 Comparison of Experimental and Calculated Dial Readings for various Temperatures @ 2000 psi and 300 rpm

Figure 4.8 - Comparison of Experimental and Calculated Dial Readings for various Temperatures @ 8000 psi and 6 rpm

Discussion of the Results:

It has been observed that, for 500, 4000 and 2000 psigs, model predicts the experimental dial readings with high accuracy for all shear rates as long as the temperature is below 200 °F. The only exception to this fact is observed for 4000 psig, 6 rpm readings where model over predicted the experimental results with errors of about 20-90 %. As a conclusion, between 500-4000 psig, model predicted the experimental values with errors lower than 15 %, as long as the temperature is lower than 200 °F. The difference between measured and calculated dial reading values becomes high at lower shear rate values. The main reason for such inconsistency is because the Arrhenius equation which is a monotonous decreasing function, is not fully able to represent the behavior of the fluid for all ranges of temperature and shear rates. A closer look at the data shows that, although the general trend of the fluid's dial readings is monotonously decreasing with increasing temperature, at lower shear rates sometimes dial readings do not change with temperature or even increase as temperature is increased. These behaviors are observed at high temperature-low shear rate values where dial readings are fairly small. It might be the case that wrong readings are measured at these temperatures and shear rates.

For higher operating pressures (8000 and 12000 psigs) it was observed that model predicted the experimental values with high accuracies at all temperatures as long as shear rate is higher than 6 rpm. However, at lower shear rates (6 and 3 rpm) model over predicted the experimental values in almost all temperature

conditions. The reason for such inconsistency might be due experimental recording error as mentioned above.

4.2.2 Experimental Studies with the PVT Apparatus

The density of synthetic based drilling fluids is sensitive to down hole conditions. Therefore, in order to get accurate pressure losses, not only rheological behavior of drilling fluids but also densities should be corrected for well bore conditions.

Mercury free PVT system is used for this purpose. By using this system, volume of the cell at different temperature and pressure conditions can be determined. As a result of that, not only density variation but also the compressibility of the fluid as a function of pressure and temperature can be determined.

The diagram of the apparatus can be seen in Figure 4.9. PVT Cell has an inner diameter of 2.500" and outer diameter of 5.500". It is divided into two by a hydraulic piston. The piston is connected to a rod that is attached to "Linear variable differential transducer (LVDT)". LVDT is used to measure the position of piston hence the volume of the sample in the cell. Preliminary calculations showed that the minimum volume that is needed in the cell before sample start pushing piston is 88 ml. In other words, the total volume compressed in the cell is whatever the volume that LVDT reading correspond plus 88 ml of minimum volume. In order to increase the pressure in the cell, oil is injected to the hydraulic oil side of the piston. In order to increase the temperature of the cell, oven in which the PVT cell is mounted should be used.

The oven is a forced-air oven and its temperature is controlled with a microprocessor controller. The maximum working temperature of oven is 500°F. However, the temperature limit for the linear differential transducer is 300°F and for that reason it is anticipated to go as high as to 280°F. Working pressure of the cell is 10000 psig and it is planned to go as high as 6000 psig.

In order to determine the accuracy and sensitivity of temperature sensors, pressure transducers and (LVDT) calibration experiments with water at different temperatures and pressures are conducted. This part of the report covers the experimental procedure and the results obtained from the calibration tests.

Figure 4.9- Schematic view of PVT cell and Sampling Lines

Calibration Tests:

Deionized distilled water is used as calibration fluid. The process of placing sample in to the PVT cell is very important. The main purpose is to get the all the air that might be in the cell and sampling lines before injecting the sample since presence of air in the cell can severely affect the results.

Experimental Procedure:

1. Piston should be pushed down to the bottom of the cell with injecting sample from the accumulator to the cell.
2. Evacuate the cell and sampling valves through valve # 1 using a vacuum pump.
3. Once the cell and sampling valves are evacuated, close valve #1 and allow sample from accumulator to enter to the sample lines and cell.
4. During this process, the pressure in the cell would increase while fluid is filling the cell. Once all the fluid in the accumulator is injected to the cell, open valve #1 and inject oil to the hydraulic side of the cell.

5. This would provide bleeding any air that might be trapped in fittings. Once line between valve #2 and valve #1 is full of water, isolate your sample in the cell from sampling lines.
6. Record LVDT position as your initial position and increase the pressure on the sample by injecting oil to the hydraulic side of the system. Control the pressure on the hydraulic oil side by adjusting the back pressure valve.
7. Record LVDTs at different pressure conditions and then determine the volume of the sample at each pressure condition.
8. In order to determine compressibility at different temperatures, oven should be set to the desired temperature.
9. As temperature increases, the pressure in the cell increases as well due to sample expansion. The pressure in the cell should be maintained by using the back pressure valve.
10. Once the temperature in the cell has reached the desired temperature, back pressure valve should be closed and experiments at various pressures can be done.

Once volume change of sample with different pressures and temperatures is known, density of the sample can be determined since the mass of the sample in the cell is always constant during experimentation period.

In order to determine the accuracy of data acquisition system, density of water is determined under different pressure and temperature conditions (Figures 4.10-4.12).

Figure 4.10- Comparison of Measured and Published Water Densities @ Various Pressures @ T= 70°F

Figure 4.11- Comparison of Measured and Published Water Densities @ Various Pressures @ T= 120°F

Figure 4.12 - Comparison of Measured and Published Water Densities @ Various Pressures @ T= 200°F

As it is seen from figures 4.10-4.12, the difference between theoretical densities and experimental densities are always lower than 1% and mostly lower than 0.5%. It is known that the volume measurement accuracy of the LVDT transducer is $\pm 0.5\%$ which is even more than the error that is determined in calibration experiments.

In the next step, the experiments with base synthetic oil and synthetic based drilling fluid will be conducted. The test matrix for these experiments is given on Table-4.4.

Table 4.4 - Test Matrix for the Experimental Study of Synthetic Based Oils & Drilling Fluids with PVT Apparatus

Temp., °F	Applied Pressure at each Temperature											
80	500	1000	1500	2000	2500	3000	3500	4000	4500	5000	5500	6000
120	500	1000	1500	2000	2500	3000	3500	4000	4500	5000	5500	6000
160	500	1000	1500	2000	2500	3000	3500	4000	4500	5000	5500	6000
200	500	1000	1500	2000	2500	3000	3500	4000	4500	5000	5500	6000
240	500	1000	1500	2000	2500	3000	3500	4000	4500	5000	5500	6000
280	500	1000	1500	2000	2500	3000	3500	4000	4500	5000	5500	6000

APPENDIX-A:

Relation Between Coefficient $C_1(P)$ and Shear Rate:

$$C_3(g) = 0.0371 \ln(g) + 0.0039 \dots\dots\dots (A-1)$$

$$C_4(g) = 4.289 \times 10^{-5} * \log 10(g) - 3.476 \times 10^{-6} \dots\dots\dots (A-2)$$

$$C_5(g) = -5.926 \times 10^{-10} + 8.499 \times 10^{-09} * \log 10(g) \dots\dots\dots (A-3)$$

$$C_6(g) = -6.636 \times 10^{-14} + 4.436 \times 10^{-13} * \log 10(g) \dots\dots\dots (A-4)$$

Among these equations, equation that has been used to define the relation between C_3 and γ (equation A-1) approximates the actual C_3 coefficients with high accuracies (lower than 6% absolute error). However, the other relations used to relate shear rate to coefficients are not that accurate, especially at low shear rates (Table A1-A2). This might be because of the fact that low shear rate and high shear rate behavior of the fluid is not the same. If this is the case then low shear rate and high shear rate analysis of the fluid should be done separately and two functions should be used instead of one to show the behavior of dial readings with pressure, temperature and shear rate.

TABLE A-1 - Correlation Between Coefficient 'C3' and Shear Rate

Shear Rate	C3	C3-calculated	Error, %
600	0.251	0.24122609	3.893987965
300	0.21	0.21551033	2.623966576
200	0.195	0.200467574	2.803884256
100	0.174	0.174751814	0.432076954
6	0.075	0.070374276	6.167631589
3	0.043	0.044658516	3.857013743

TABLE A-2 – Correlation Between Coefficient 'C4' and Shear Rate

Shear Rate	C4	C4-calculated	Error, %
600	1.15E-04	0.000115679	8.53E-01
300	1.04E-04	0.000102768	8.03E-01
200	9.42E-05	9.52152E-05	1.06E+00
100	8.72E-05	0.000082304	5.60E+00
6	1.29E-05	2.98989E-05	1.31E+02
3	3.02E-05	1.69877E-05	4.37E+01

TABLE A-3 – Correlation Between Coefficient 'C5' and Shear Rate

$$C5 (RPM) = -5.926e-10 + 8.499e-09 * \log_{10} (RPM)$$

Shear Rate	C5	C5-calculated	Error, %
600	2.26E-08	2.30189E-08	1.72E+00
300	2.07E-08	2.04605E-08	1.06E+00
200	1.87E-08	1.89639E-08	1.36E+00
100	1.75E-08	1.64054E-08	6.25E+00
6	3.53E-09	6.02091E-09	7.06E+01
3	5.28E-09	3.46245E-09	3.44E+01

TABLE A-4 Correlation Between Coefficient 'C6' and Shear Rate

Shear Rate	C6	C6-calculated	Error, %
600	1.15E-12	1.17E-12	1.22E+00
300	1.05E-12	1.03E-12	1.29E+00
200	9.39E-13	9.54E-13	1.68E+00
100	8.64E-13	8.21E-13	4.94E+00
6	1.74E-13	2.79E-13	6.02E+01
3	2.23E-13	1.45E-13	3.50E+01

Correlation Between Coefficient $C_2(P)$ and Shear Rate:

Similar analysis has been conducted to determine the effect of shear rate on coefficient C_2 using the coefficients C_7 , C_8 , C_9 and C_{10} . The relations between these coefficients and shear rate are determined as follows as a result of extensive non-linear regression analysis process.

$$C_7(g) = 177.307 * (1 + g)^{(-0.1009353)} \dots\dots\dots (A-5)$$

$$C_8 = 0.025 \dots\dots\dots (A-6)$$

$$C_9(g) = 5.674 \times 10^{-6} + 7.083 \times 10^{-7} * \log_{10}(g) \dots\dots\dots (A-7)$$

$$C_{10}(g) = 2.284 \times 10^{-10} + 6.616 \times 10^{-11} * \log_{10}(g) \dots\dots\dots (A-8)$$

It has been found out that, the above relations approximated the relation between shear rate and coefficient C_2 with high accuracy. Absolute errors associated with the above relations are always smaller than 10 % even at low shear rates (Table 5A-8A)! The reason for this might be the fact that, third degree polynomial in equation (5) approximates behavior of coefficient of C_2 much better

than it does for coefficient C_1 . It should be also noted that, among these coefficients, C_8 is almost constant for various shear rates so it can be taken as constant as shown in equation (A-6).

TABLE A-5 Correlation Between Coefficient 'C7' and Shear Rate

Shear Rate	C7	C7-calculated	Error, %
600	95.649	92.94785102	2.82402219
300	100.493	99.66691802	0.822029371
200	102.854	103.8130849	0.932472142
100	109.196	111.2805088	1.908960732
6	139.863	145.6886294	4.165239817
3	159.649	154.1547019	3.441486053

TABLE A-6 Correlation Between Coefficient 'C8' and Shear Rate

$C_8(\text{RPM})=0.025$

Shear Rate	C8	C8-calculated	Error, %
600	2.50E-02	0.025	0.00E+00
300	2.60E-02	0.025	3.85E+00
200	2.60E-02	0.025	3.85E+00
100	2.90E-02	0.025	1.38E+01
6	2.10E-02	0.025	1.90E+01
3	2.90E-02	0.025	1.38E+01

TABLE A-7 - Correlation Between Coefficient 'C9' and Shear Rate

Shear Rate	C9	C9-calculated	Error
600	7.27E-06	7.64176E-06	5.11E+00
300	7.41E-06	7.42854E-06	2.77E-01
200	7.38E-06	7.30382E-06	1.01E+00
100	7.71E-06	7.0906E-06	8.03E+00
6	5.62E-06	6.22516E-06	1.08E+01
3	6.32E-06	6.01194E-06	4.84E+00

TABLE A-8 - Correlation Between Coefficient 'C10' and Shear Rate

$$C10(RPM)=2.284e-10+6.616e-11*\log_{10}(RPM)$$

Shear Rate	C10	C10-calculated	Error, %
600	3.87E-10	4.12202E-10	6.59E+00
300	3.91E-10	3.92286E-10	4.06E-01
200	3.87E-10	3.80636E-10	1.64E+00
100	3.98E-10	3.6072E-10	9.30E+00
6	2.61E-10	2.79882E-10	7.36E+00
3	2.63E-10	2.59966E-10	1.19E+00

5. STUDY OF CUTTINGS TRANSPORT WITH FOAM UNDER LPAT CONDITIONS

Investigator: Evren Ozbayoglu

5.1 Objectives

- To investigate foam rheology and flow behavior in pipe and annulus.
- To determine (experimentally) and to predict (numerically) frictional pressure losses (with and without cuttings) and volumetric requirements (injection rate, injection pressure and backpressure) for effective cuttings transport with foam flow in inclined and horizontal wellbores.

5.2 Project Status

Project activities for the Task 6 have been focused on the development of the simulator for pressure loss estimation during foam flow in pipes and annuli. Some foam flow experiments have also been conducted and results are given in the following section.

5.2.1 Computer Program

A computer program has been developed to evaluate frictional pressure losses during the flow of foam in horizontal pipes and annulus. Basically, the simulator divides the pipe into small cells in axial direction, and performs necessary calculations for each cell. The idea is, in a single cell, the fluid properties are assumed to be constant, i.e., the quality, viscosity, velocity does not vary in axial direction in the cell. Since the length of a single cell is infinitesimal, the assumption is acceptable with not much loss from accuracy. Initial conditions (i.e. temperature, inlet pressure, inlet flow rates for liquid and gas phase) are defined by the user. The simulator determines the frictional pressure drop for the first cell, and then determines the new pressure input for the next cell. Since there is a change in pressure, there will be a change in quality of the foam. Also, because of the compressible phase, there will be a gas expansion due to pressure drop in axial direction which leads to a change in flow rate and velocity as well. So, simulator determines the new velocity, quality, rheological parameters, etc for the next cell, and determines the frictional pressure drop again.

So, the output of a cell is the input of the next cell. Finally, the computer gives an output of initial and final velocities, qualities and pressures.

5.2.2 Foam Flow Experiments

Preliminary foam flow experiments have been conducted. The experimental data obtained is given in the appendix. The experiments are conducted for 70%, 80% and 90% qualities and for total flow rates approximately 110 gpm, 190 gpm, 270 gpm and 340 gpm.

It was observed that, at low flow rates, the agitation process is not properly achieved because of low turbulence. So, a stratified liquid layer is occurred. For preventing the stratified liquid layer, an additional mixer section was added to improve agitation of liquid and gas phase for generating foam. The schematic drawing of the additional mixing assembly is shown in Figure 5.1.

Figure 5.1 - Schematic Drawing of the Additional Mixing Assembly

Experimental Results

The results are presented in Figures 5.2 - 5.5. Generally, it can be observed in all plots that the increase in quality causes an increase in frictional pressure loss

The detailed analysis of the experimental results as well as more foam flow experiments are in progress.

A complete rheological characterization of the foam is needed in order to compare experimental results with ones from theoretical models. Analysis of the data in Figures 5.2-5.5 revealed that data are needed in order to determine the rheological parameters more accurately. Some experiments will be carried out again to verify the repeatability of the data.

Once the rheological characterization of the foam is completed, experimental pressure loss results will be compared to the ones obtained from

available models in the literature. It is obvious that, every foam has its own rheological parameters due to the surfactant used for generating foam, variations in gas and liquid properties used in foam, etc. So, the next step will be determination of rheological parameters.

Figure 5.2– Experimental data for 2 inch pipe

Figure 5.3 – Experimental data for 3 inch pipe

Figure 5.4 – Experimental data for 4 inch pipe

Figure 5.5 – Experimental data for 8 inch – 4.5 inch annulus

6. STUDY OF CUTTINGS TRANSPORT WITH AERATED MUDS UNDER LPAT CONDITIONS

Investigator: Paco Vieira

6.1 Objectives:

1. Determine experimentally the minimum flow rates for water and air that guarantee the hole cleaning while drilling horizontal and near horizontal sections.
2. Develop charts that help to establish minimum requirements of air and water injection rates to plan drilling of high angle and horizontal sections using air-water system as drilling fluid.

6.2 Project Status

Activities for Task 7 have been focused on searching more literature on the three-phase flow in pipes and annuli and more experiments with air-water-cuttings mixture. The results are given in the following section.

6.2.1 Literature Review

Gillies et al. [1997]¹ presents the results of experiments conducted in order to investigate the ability of gas liquid mixtures to transport sand in a horizontal pipe or well at low velocities. Using a experimental flow loop approximately 30 m in length the addition of gas in laminar and turbulent liquid flow regimes were investigated in a predominantly slug flow regime. One of the main conclusions of the study is that the gas injection has a little influence on the ability of a laminar flow to transport sand at low superficial velocities. This is due to the fact that the gas and the solids travel in different regions of the pipe. They also observed that the gas injection increases the solid transport rate and the axial pressure gradient when the liquid flow is turbulent.

Kamp and Riviera [1999]² presented a paper where a review on the state of the art of mechanistic modeling of cuttings transport was presented. They also developed a mathematical treatment of cuttings transport in two layers simulating a moving bed of packed cuttings below a heterogeneous layer of mud and cuttings. The model was used to perform numerical simulation, predicting bed heights, pressure drops and transport velocities at different rates of penetration and mud flow rates. Results were compared by empirical correlation-based models. The differences were discussed and improvements on the current model were proposed

Xiao et al. [1990]³ presented a paper where a mechanistic model for flow pattern and pressure drop prediction for flow in pipes were developed. The model

simulates 1-D steady state flow of air and liquid. This model is applicable for the flow of gas and liquid in horizontal and near horizontal pipe pipes. The model uses Barnea's liquid holdup criteria of 35% for determination of transition of stratified wave flow into slug flow versus annular. The model was validated against a comprehensive database and shown be particularly strong for predicting intermittent flow regime pressure drops.

Doron et al. [1986]⁴ investigated the hydraulic transport of coarse particles in horizontal pipes. A physical model for the prediction of the pressure drop and flow patterns were presented. They analyzed the pressure drop behavior of slurry flow and various flow patterns by using a two-layer model. They assumed that for each layer the flow was represented by means of the average properties and no slip between the two phases. The proposed model was compared with new experimental data showing good agreement. The model was also compared with other correlations.

Barnea et al. [1986]⁵ presented a paper where he investigated the effect of gas injection on the flow of liquid-solid mixtures. Using an experimental facility he observed that the gas injection had two different effects on the pressure drop. The first effect is a reduction on the pressure drop due to formation of gas voids for a constant total flow rate. The second effect is a pressure drop increased due to the acceleration losses associated with the slug flow. Finally it is concluded that the addition of gas, combined with an pipe diameter increase may be a practical way to reduce the pressure drop for a given slurry flow rate.

Tippetts and Priestman [1997]⁶ presented the results of pipe flow experiments conducted by using a horizontal transparent flow loop with water, air and sand. They have developed flow pattern maps based on the superficial velocities of water and air. They observed that the demarcating line between solid mobility and stasis can be discerned and have a very strong influence of slugs flow regimes.

Matthew et al [2000]⁷ presented a paper describing some experiments performed at the BP Amoco 6" multiphase flow facility located at Sunbury. Several fluids were selected for these experiments to examine the influence of liquid viscosity on the results. These were water, oil and two different Carboxy Tethy and Cellulose solution (150 and 300 cp.). Their results showed that, in slug flow, water and low viscosity oil was able to transport the solids. They also presented a model for solid transport based on the concept of minimum transport velocity, the velocity, which is sufficient to remove particles from a settled bed. The model used a criteria for solid transport for single phase (liquid) as suggested by Thomas [1962]⁸ where establishing a minimum pressure gradient is required to transport of solid occurs.

They defined a friction velocity for particle smaller than the viscous sub layer thickness as follows:

$$U_o = \left(100 * w_s * (v/d)^{2.71}\right)^{0.269}$$

Where w_s is the particle settling velocity under quiescent condition, v is the kinematic viscosity and d is the particle diameter.

For particles greater than viscous sub layer thickness :

$$U_o = \left(0.204 * w_s * \left(\frac{v}{d}\right) * \left(\frac{v}{D}\right)^{-0.6} \left(\frac{r_s - r_l}{r_l}\right)^{-0.23}\right)^{0.714}$$

Where D is the pipe diameter, ρ_s is the solid density and ρ_l is the liquid density.

The laminar sub-layer thickness is determine by:

$$d = 62 * D \left(\frac{D * U_{sl} * r_l}{m_l} \right)^{-\frac{7}{8}}$$

Where U_{sl} is the superficial liquid velocity.

The other variable required for calculation of the friction velocity is the settling velocity of particles under quiescent condition. This is dependent on Reynolds number and can be divided into three regimes- Stokes's law regimes, an intermediate region and the Newton's law regime. The particle Reynolds number is defined as:

$$Re_p = \frac{d * w_s * r_l}{m_l}$$

For $Re_p < 2$ (Stoke's Law region)

$$w_s = \frac{g * d^2 * (r_s - r_l)}{18 * m_l}$$

For $2 < Re_p < 500$ (Intermediate Region)

$$w_s = \frac{g * d^2 * (r_s - r_l)}{3 * r_l * \left[\frac{24}{Re_p} (1 + 0.14 * Re_p^{0.7}) \right]}$$

For $Re_p > 500$ (Intermediate Region)

$$w_s = 1.74 * \sqrt{\frac{g * d * (r_s - r_l)}{r_l}}$$

Finally, the pressure gradient for minimum transport to occur is calculated by:

$$\frac{\Delta P}{\Delta x} = \frac{4 * r_l * (U_c)^2}{D}$$

If the pressure drop gradient predicted by a multiphase flow pressure drop model is greater than the pressure gradient predicted by the equation, the particles will be transported.

6.2.2 Three Phase Flow Experiments

Tests were conducted using total flow rates of 200, 300, 400 and 500 GPM for the horizontal position (90 degrees from vertical) and simulating a constant drilling rate of 30 ft/h. The liquid flow rate was decreased while air flow rate was increased in order to maintain the total flow rate constant. The amount of cutting in the test section was recorded and the steady state bed height was measured. The flow patterns were also observed for each combination of liquid and gas flow rate. The results from the experimental tests for total flow rate of 200, 300 and 400 GPM are given in Figures 6.1 – 6.13.

For total flow rates of 200, 300 and 400 GPM it was observed that no matter what the combination of gas and liquid flow rates are, there is always a steady state cutting bed formed (Figures 6.1, 6.4, 6.7). When 500 GPM of liquid rate was used, it was observed that a moving bed was formed in the test section for the horizontal position at ROP of 30 ft/h. Uniform bed was never observed under this condition (Figure 6.10). Stable-cutting beds were formed, however, for the different combinations of air and liquid when the total flow rate is 500 gpm (Figure 6.11).

In all the experiments, it was observed that as the gas/liquid ratio increases the bed height also increases (Figures 6.2, 6.5, 6.8, and 6.12).

It was also observed that, though the bed height is increased and the open area to flow is reduced, the average pressure frictional pressure drop in the test section is reduced as the gas injection rate is increased (Figures 6.3, 6.6, 6.9., and 6.13).

Based on the initial experimental results, it was seen that there is no optimal conditions where the cuttings bed removed completely. Therefore, it was decided to modify the test matrix for higher flow rates. The modified test matrix is shown in Table 6.1.

Table 6.1 - Modified Test Matrix

ROP (ft/h)	30		50		70							
Inclination	90		80		70							
Total Flow Rate (GPM)	200		300		400		500		600		700	
	Water (GPM)	Air (GPM)	Water (GPM)	Air (GPM)	Water (GPM)	Air (GPM)	Water (GPM)	Air (GPM)	Water (GPM)	Air (GPM)	Water (GPM)	Air (GPM)
	200	0	300	0	400	0	500	0	500	100	500	200
	100	100	200	100	300	100	400	100	400	200	400	300
			100	200	200	200	300	200	300	300	300	400
					100	300	200	300	200	400	200	500
							100	400

Figure 6.1 - Accumulation of cutting in the test section for a Total Flow rate of 200 GPM

Figure 6.2- Bed Height Vs Gas Volumetric Fraction for total flow rate of 200 GPM

Figure 6.3- Variation of Frictional Pressure Drop for total flow rate of 200 GPM

Figure 6.4- Accumulation of cutting in the test section for a Total Flow rate of 300 GPM

Figure 6.5- Bed Height Vs Gas Volumetric Fraction for total flow rate of 300 GPM

Figure 6.6- Variation of Frictional Pressure Drop for total flow rate of 300 GPM

Figure 6.7- Accumulation of cutting in the test section for a Total Flow rate of 400 GPM

Figure 6.8- Bed Height vs. Gas Volumetric Fraction for total flow rate of 400 GPM

Figure 6.9- Variation of Frictional Pressure Drop for total flow rate of 400 GPM

Figure 6.10- Accumulation of cutting in the test section for a Total Flow rate of 500 GPM-only liquid.

Figure 6.11- Accumulation of cutting in the test section for a Total Flow rate of 500 GPM

Figure 6.12- Bed Height vs Gas Volumetric Fraction for total flow rate of 500 GPM

Figure 6.13- Variation of Frictional Pressure Drop for total flow rate of 500 GPM

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7. STUDY OF FOAM FLOW BEHAVIOR UNDER ELEVATED PRESSURE AND ELEVATED TEMPERATURE CONDITIONS

Investigator: Affonso Marcelo Fernandes Lourenco

7.1 Objectives

1. Perform experimental study of foam flow behavior inside pipes and annuli in a large-scale loop (ACTS) under elevated pressure and temperature.
3. Develop empirical correlations to estimate pressure losses during foam flow under given gas-liquid ratio, temperature and pressure conditions.

7.2 Project Status

During the past three months, activities related to Task 9 have been focused on the design of flow loop modifications to accommodate foam flow, foam stability experiments, and foam pressure volume temperature (PVT) analysis.

7.2.1 Design Considerations for ACTS Flow Loop Modification for Foam Flow

Critical issues of ACTS flow loop design for foam flow were identified as the performance of the tri-phase Moyno pump for pumping foam, foam making and breaking system, temperature control and cuttings injection system. Efforts have been spent to identify all the necessary equipment and come up with the optimum system's configuration to conduct successful foam flow experiments under elevated pressure and temperature.

A summary of the design considerations and the possible problem areas in pumping cuttings with foam is given in the following section.

Multiphase Pumping

The idea of generating foam before the pumping system was introduced. The reason for this modification was based on possible difficulties of the pumping system in handling the liquid and gas phases independently (i.e. possibility of gas slippage)

Moyno pump showed good performance in pumping foam for small pressure drop between suction and discharge ends. Performance of the Moyno pump under the high differential pressure across the pump, however, still needs to be seen.

The piston pump was considered inadequate for pump and pressurize foams for elevated pressure drops across the equipment.

Foam Generation

According to the experiments performed in Halliburton using the small scale facility, the foam properties change considerably over a while a transient period depending upon the shear rate induced during its generation. This effect shall be considered to avoid measurements during the cited transient period.

Another remark was about the configuration used in the reduced scale facility, where the liquid stream was injected into the gas, and not the other way around.

Foam Breaking System

The installation of a surge tank to allow a quick depressurization of foam was suggested. The abrupt expansion of foam bubbles would break them and free considerable amount of gas from the system. In addition, this procedure would allow the foam breaking equipment, where foam breaker is injected into the foam, to operate at lower pressure. The liquid part coming from the second defoam operation may contain small gas bubbles dissolved in it, and this could regenerate foam after the final decompression step. The lower pressure conditions would minimize this possible problem.

It was also suggested that there is a need for an investigation on the availability of foaming and defoaming agents, and the optimum amount of defoamer to break the foam. The foaming agent does not offer problems to its disposal. The same is not true for the defoaming agents, and disposal procedure shall be developed depending on the actual concentrations and chemical composition.

Cuttings Injection

The location and operating range of the cuttings injection tank was discussed. The pressure rating of the injection vessel is going to be an important design parameter in this case and therefore, should be carefully evaluated.

The test procedures accounting for different loop designs are still under development.

7.2.2 Foam Stability Experiments

Tests to evaluate the stability of foam generated by Bachman's foaming agent in the presence of salt and oil were performed. Mineral Salt concentrations in the range of 5 to 30% w/v were used. The influence of 5% v/v of mineral oil was also tested. Most of tests were repeated for accuracy. Additional tests will be performed. The test matrix is shown in Table 7.1.

Table 7.1 – Test Matrix

Case Studied	Number of Tests
Water + Bachman foamer 1% v/v	2
Water + Bachman foamer 1% v/v + 5% w/v mineral salt	3
Water + Bachman foamer 1% v/v + 10% w/v mineral salt	2
Water + Bachman foamer 1% v/v + 20% w/v mineral salt	2
Water + Bachman foamer 1% v/v + 30% w/v mineral salt	1
Water + Bachman foamer 1% v/v + 5% v/v mineral oil	1

Test Procedure

In all the tests, a 100 ml of 1% v/v foamer solution has been prepared. The foam is formed by mixing the foamer solution with a regular blender for 1 min. For the tests containing oil or salt, the desired amount of each contaminant was added to the foamer solution and then foam was created. Typically 600 to 750 ml of foam was created corresponding to initial qualities of 84 to 87%. The foam was transferred to a graduated cylinder and the clock was started immediately. The volume of drained water was recorded after 1 and 2 minutes, and after that the time was recorded for each 5 ml volume of drained liquid.

Results

The foam stability was measured by using two different parameters: half life time and drainage rate. The half time life is the time when half of the foamer solution volume is drained. High half life time values indicate a more stable system. The stability of a foam system can also be evaluated by measuring the drainage rate when the half of the liquid volume is drained. Drainage curves obtained by plotting drained liquid volume versus time can be used to evaluate drainage rate. The drainage rate is defined as follows:

$$DR = \frac{kV_o}{2}$$

where V_o is the initial foamer solution volume and k is the the time constant. The time constant k can be calculated by approximating the liquid drainage curve using first order kinetic equation:

$$V = V_o(1 - \exp(-kt))$$

A graph of $\ln((V_o - V)/V_o)$ versus time is used to compute k for a specific foam system. Figure 7.1 shows the drained volume curve for foam without salt and oil.

Figure 7.2 shows the change of drained liquid volume with time for foam containing salt. The half life time and drainage rate are shown in Figure 7.3 for

the same system. Results indicate that stability is not considerably affected by the salt presence up to 20% w/v. Figure 7.3 also shows an enhancement in foam stability when salt concentration increases from 5 to 20%. Although the half life time value indicates a clear decrease in foam stability for 30% w/v of salt, the drainage rate does not show the same behavior. More experiments are needed to confirm these results. Figure 7.4 shows that salt concentrations greater than 5% w/v seem to affect the foamability or capacity to generate foam.

Figure 7.5 shows drainage curve for foam with 5% v/v concentration of mineral oil. Figure 7.6 shows half life time and drainage rate as compared to the foam with no oil or salt. The oil presence enhanced foam stability. One of the reasons for this result is the increase in liquid phase viscosity. This increment of viscosity tends to increase the time that liquid phase takes to cross the path between gas bubbles and get out of the foam.

7.2.3 PVT Analysis for Foam

The compressibility of foam has been tested using the PVT cell. A test procedure was developed. However, further improvement is needed. A schematic drawing of PVT test development is shown in Figure 7.7

Test Procedure

- Inject water into the PVT cell chamber by performing operation number 1 in the schematic drawing. The piston should be moved all the way back to its maximum position (3 inches in the displacement reading).
- Release remaining pressure from inside PVT cell chamber opening valve 4.
- Move PVT cell to downward position using the electrical drive system. The oven doors must be closed for this operation.
- Open main front cap and remove all remaining water from the chamber.
- Connect a flexible hose to valve 6 (open) and inject air in the line to remove any trapped water through valve 4 (open).
- Close valves 6 and 4 and dry PVT cell chamber.
- Bring the PVT cell upward position.
- Prepare 150 ml of foamer solution with concentration 2% v/v.
- Blend the solution for 30 s.
- Transfer manually, as much as possible, all the foam into the PVT test chamber.
- Keep any remaining foam volume for further volumetric calculation.
- Close, as soon as possible, the PVT chamber with the main cap.
- Bring the PVT cell downward position.
- Inject air at 80 psi by using the flexible hose into valves 6 and 4 for 2 min. Air supply valve, valve 6 and valve 4 must be opened respectively.
- Bring PVT cell horizontal position.
- Compress foam sample by performing operation 3 in schematic drawing.

- Measure pressure and displacement of piston (indirect volume measurement) within specified intervals.
- Release PVT cell pressure by opening valve 4 and 6 respectively.
- Open Main cap and dry cell.

One test was performed and repeated. Part of the raw data including PVT piston displacement and pressure inside the PVT cell chamber are shown in Table 7.2. The test will be repeated and data analyzed allowing the comparison of different equations of state for foam against experimental data.

Table 7.2 – PVT Test Data of Foam

Test 1			
PVT	Cell	Pressure	LVDT Reading
(psig)			
76			3.03
80			2.72
100			1.57
121			0.69
140			0.1
159			-0.35
180			-0.77
200			-1.08
220			-1.34
240			-1.55
260			-1.64
279			-1.90
303			-2.06
320			-2.17
350			-2.34
360			-2.39
380			2.49
400			-2.57
420			-2.64
440			-2.71
460			-2.77
480			-2.83
503			-2.89
550			-3

Note: LVTD reading refers to the PVT cell piston displacement. It varies from approximately -3 to 3 representing a 6 in displacement.

Foam Equation of States

Among the equations of state found in the literature we can cite David and Mardsen¹. They proposed a simple equation for the compressibility of foam:

$$C_F = C_G \Gamma$$

Where C_F is the compressibility of foam, C_G is gas compressibility and Γ is foam quality. This equation can be used as an equation of state when pressure/volume dependence of both quality and C_G is established.

Huey and Bryant² proposed the follow equation of state:

$$P = \left(\frac{1}{\rho} - \frac{1}{1+\beta} \cdot \frac{1}{\rho l} \right) = S \cdot T$$

where ;

$$S = \beta \left(\frac{R}{1+\beta} \right)$$

$$\beta = \frac{mg}{ml}$$

mg : mass of gas phase
ml : mass of liquid phase

This equation of state was developed considering an ideal gas-phase behavior.

Lord³ et al. also proposed an equation of state using the definition of quality and the engineering gas law:

$$PV_F = bP + a$$

where

$$a = \frac{W_g ZRT}{M}$$

W_g – foam quality
 M – gas molecular weight

$$b = (1 - W_g) \hat{V}_F$$

V_F – foam volume per unit mass

Other equations of state with little applicability from the engineering point of view can be cited as the one proposed by Ross⁴:

$$(P_s - P_{gf})V_F + \frac{2}{3}\sigma\alpha = nRT_{gf}$$

where

P_s –surrounding's pressure

P_{gf} – gas phase pressure

α -interfacial area per unit volume

σ - liquid surface tension

References

1. David, A. and Marsden, S.S.Jr.: "The Rheology of Foam", SPE 2544, 1969.
2. Huey, C.T and Bryant, R.A.A: "Isothermal Homogeneous Two-Phase Flow in Horizontal Pipes", Aiche J., 1967, v.13, 70.
3. Lord, D.L.: "Analysis of Dynamic and Static Foam Behavior", SPE 7927.
4. Ross, S: "Bubbles and Foams", *Ind. Eng. Chem.* , 1969, 61,48.

Figure 7.1– Drained Liquid Volume – Foamer Solution 1% v/v (with no salt or oil).

Figure 7.2 - Drained Liquid Volume – Salt Concentration Effect.

Figure 3 – Drainage Rate and Half Life Time of Foam with Salt

Figure 7.4 – Foamability as a Function of Salt

Figure 7.5 – Drainage Rate and Half Life Time of Foam with Oil

Operation	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1 Inject sample into PVT cell	C	C	O	C	O	C	O	**	C	C	O	C	O	O	C	C
2 Bleed air from PVT sample	O	O	O	O	O	C	*	**	C	C	C	O	C	C	C	C
3 Pressurize sample in PVT cell	C	C	O	C	C	C	*	**	O	C	C	O	C	C	C	C
4 Push sample from PVT cell to accumulator	C	O	O	O	O	C	*	**	C	C	O	O	C	O	C	C
5 Lower piston in accumulator	C	O	O	O	O	C	O	O	C	O	C	C	C	O	C	O
6 Move PVT piston to the right	C	O	O	O	O	C	O	**	C	C	O	C	O	C	O	C
7 Move PVT piston to the left	C	O	O	O	O	C	*	**	C	C	O	O	C	O	C	C

* Apply back pressure to oil side as required
 ** Operate air pump as required

Figure 7.6 – Schematic Drawing of PVT Cell

8. DEVELOPMENT OF CUTTINGS MONITORING METHODOLOGY

INVESTIGATORS: Kaveh Ashenayi, Gerald Kane, Len Volk, Neelima Godugu, Tsri Suresh

8.1 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 drill pipe. There are four different techniques that could be examined. However, as it was pointed out in the previous report only three have good potential for success. These are:

1. Ultrasound
2. X-Ray/Gamma-Ray
3. Optical

8.2 PROGRESS REPORT

A PC (Pentium III – 450 MHz) based data collection system has been assembled. The system uses a DAC (PCL-818HG) designed by Advantech, Inc. The following are the card features:

- 16 single-ended or 8 differential analog inputs
- 100kHz 12-bit A/D conversion
- 1 K word FIFO
- Programmable gain for each input channel (up to 1000)
- Automatic channel/gain scanning with DMA
- 16 digital inputs and 16 digital outputs
- One 12-bit analog output channel
- Programmable pacer/counter
- Free DOS driver/Windows DLL driver included
- Software support from VisiDAQ 3.1, ActiveDAQ, LabVIEW, and Windows 3.1/95/NT High Speed DLL drivers.

The operating system used is the Windows/NT workstation.

We have developed and are in the process of debugging the software needed for data collection. This is a MS-VB based application that controls the data sampling and data storage. Data is stored in a MS-Access database for analysis.

The DAC and the VB application are working correctly and we have the capability of displaying the data collected (either in a table or as a plot) as well as storing the data. We are in the process of addressing a small problem we have encountered. The expansion card that would have allowed us to connect as many as 32 sensors to the same board is not functioning correctly. We are working with the DAC vendor's technical support to solve the problem.

This problem will not stop us from testing the static cell unit. We need this feature for the full system. Then we need to connect a large number of sensors. Without this expansion board we need to have a large number of DACs to handle all the sensors.

We have continued to update the sensor database. An ultrasound sensor has been identified and we are in the process of ordering it.

We have expanded our search for sensors to include gamma ray sensors as well.

Also, plans for a static cell have been completed. The manufacturing phase on the cell will start almost immediately.

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

INVESTIGATOR: Len Volk

9.1 Objective

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

9.2 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 three 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. Install the foam bubble size and distribution monitoring system on the 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.

These techniques developed under Subtask 12.2 will be applied to the drilling section of the ACTF in Subtask 12.3.

9.3 Project Status

9.3.1 Static Bubble Characterization

Microscopy. Evaluation of suitable stereomicroscopes continues. A Nikon stereomicroscope seems to offer excellent optics at an affordable price. We are waiting on an updated quote.

Illumination. In initial experiments, bubbles were easily seen using transmitted light (see figure 9.1). The layer of bubbles beneath those next to the window could be seen, but not easily. The biggest drawback with using transmitted light is the loss of light intensity as the light passes through the bubbles (distance “m” in figure 9.1) (absorption by the liquid phase and scattering at

the gas-liquid interface). In the current sample the optical length through the bubbles was ½ inch.

If the illuminating light is directed directly onto the region being observed through the microscope (but illuminated from an angle), the bubbles are almost indistinguishable (no contrast). If, however, the light is directed into the front surface of the bubbles somewhat remotely from the viewing region, the bubbles become visible, but appear very different from transmitted illumination (see figure 9.1)

Imaging. Attaching a 35mm camera to the microscope via a phototube was only marginally successful. Determining the appropriate light level using the built-in light meter was difficult at best. Several of the prints were not in sharp focus, most likely due to vibration of the camera's focal-plane shutter when operating at ½ to 1/16 second. Manufacturers of the better grade of microscopes have coped with this problem by developing their own exposure meter and shutter system. Our experience with a 35mm camera increases the attractiveness of a CCD camera.

9.3.2 Dynamic Bubble Characterization

9.3.2.1 Dynamic Imaging

Light Source. Once we purchase a microscope, we plan to “borrow” a CCD camera and verify that a pulsed laser can provide sufficient light intensity for photography. If not, we will pursue a xenon pulsed light source.

9.3.2.2 Dynamic Testing Facility

The dynamic testing facility (see last quarterly report for a schematic diagram) must be constructed of metal (pipe or tubing) if compressed air is to be used for safety reasons. Galvanized pipe can be used to 150psi. Although our corrosion resistance requirements are not high, we could expect some corrosion with galvanized pipe. Stainless pipe and fittings would be preferable, but the stainless is somewhat more expensive. We plan to begin construction next quarter.

9.4 Planned Activities

9.4.1 Static Bubble Characterization

- Purchase a microscope and begin selection of a CCD camera.
- Acquire software needed for bubble analysis.
- Depending on microscope/camera vendor, acquire Adobe PhotoShop.

9.4.2 Dynamic Bubble Characterization

- Continue pursuing a laser as an acceptable light source.
- Begin construction of the Dynamic Testing Facility.

Figure 9.1 Methods of sample illumination.

10. TECHNOLOGY TRANSFER

Meetings with Oil and Service Company Members

Efforts have been spent continuously to increase the number of industry members supporting the ACTS projects. As a result of our continuous efforts to develop more contact with oil and service companies, four new companies, namely, Petrobras has decided to join ACTS-JIP. Unocal, on the other hand, announced that they will not be able to join ACTS-JIP due to re-organization of the company and the resultant cut in their R&D budget.

c-Technical Work Groups

As part of the activities of construction work group, we have visited Phil Harris at the Halliburton research center in Duncan, Oklahoma. Phil Harris is a well known expert on foam rheology and applications. In a meeting with Dr. Harris, we have discussed our plans for flow loop modification to accommodate foam flow.

We have also visited Ohio State University multi-phase flow technology center where they have been using tri-phase Moyno pump to circulate air-liquid and solid mixtures. We had discussions with the OSU people regarding the performance of Tri-phase Moyno pump when circulating air/liquid/solid mixtures.