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Executive Summary

During this quarter, four single-phase flow comparison tests were conducted in the Small Scale Loop to investigate the effects of velocity and shear stress on paraffin deposition. Two of these tests were in the transition region between laminar and turbulent flow and two were in turbulent flow at a Reynolds number of approximately 4000. A report on all tests with South Pelto oil in the Small Scale Loop was completed and will soon be distributed to TUPDP members. Long term testing will start soon using Cote Blanche Island (CBI) oil.

Four tests were conducted in the Single-Phase Loop with Caratinga oil. This asphaltenic oil has two DSC peaks, one at 50°C and the other at 18°C. No significant deposits were generated in any of the tests. A thin layer of gelled oil was visually observed on the pipe wall; however, the thickness measurement was beyond the accuracy of our instruments. Simulation of field data is underway.

Two additional vertical two-phase tests were conducted in the Two-Phase Flow Loop with Garden Banks condensate. The purpose of these tests was to investigate the effect of high oil superficial velocities on deposit thickness. Results of these tests confirm that high oil superficial velocities resulted in thinner wax deposits. A report on all two-phase flow tests with Garden Banks condensate was completed and will soon be distributed to TUPDP members.

Modification of the Two-Phase Flow Loop to a Three-Phase Flow Loop is nearing completion. Several tests are planned during the latter part of the 1st quarter, weather permitting.

Cold finger experiments with South Pelto oil showed that wax deposit thickness decreases with an increase in water cut. Nearly all the deposition took place within the first six hours of the tests (about 80% of the deposit). Water salinity did not seem to have a significant effect on wax deposition. After tests with South Pelto oil are completed, tests with CBI oil will begin.

A mechanistic two-phase flow heat transfer model was incorporated into TUWAX, as well as viscosity tuning for multiphase flow conditions.

A Committee meeting was held December 2, 2003 in Houston to obtain additional input and/or comments from TUPDP participants. These comments were used to refine the Scope of Work for the next phase of this research program. Task charts were developed that will be utilized by the Committee for development of the detailed work plans for each task.

The next TUPDP Advisory Board Meeting will be held at the Tulsa Renaissance Hotel on April 1, 2004.

Small Scale Loop Studies

During this quarter, four single-phase flow comparison tests were conducted with South Pelto oil to investigate the effects of velocity and shear stress on paraffin deposition. The test matrix for all comparison tests is shown in Table 1. Tests with the same Reynolds number, velocity and shear stress values have now been conducted in all three diameter test sections.

The test conditions for the four new tests completed this quarter, 2003-049, 2003-050, 2003-051 and 2003-052 are presented in Tables 2-5. Two of these tests were in the transition region between laminar and turbulent flow and two were in turbulent flow at a relatively low Reynolds number of approximately 4000.

Table 1 - Test Matrix for Small Scale Loop, South Pelto Oil

(*Designates new tests this quarter)

RE	Test No.	Q (BPD)	v (ft/sec)	Shear (Pa)	Test Section (in.)
6300	2003-019	333	10.3	43.0	0.5
	2003-017	570	6.0	14.0	1.0
	2003-010	850	3.9	5.5	1.5
v (ft/sec)		**Q (BPD)**	**RE**	**Shear (Pa)**	**Test Section (in.)**
3.9	2003-050*	127	2575	7.5	0.5
	2003-049*	360	4330	6.3	1.0
	2003-010	850	6300	5.5	1.5
Shear(Pa)		**Q (BPD)**	**RE**	**v (ft/sec)**	**Test Section (in.)**
6.3	2003-051*	110	2200	3.3	0.5
	2003-052*	333	4003	3.6	1.0
	2003-010	850	6300	3.9	1.5

Table 2 - Test Conditions for Test Wax2003-049

Parameter	Value
Oil Temperature	105ºF
Oil Flow Rate	360 BPD
Oil Velocity	3.9 ft/sec
Oil Reynolds Number	4330
Glycol Temperature	75ºF
Glycol Flow Rate	1600 BPD
Facility	1.0-in. Diameter Test Section
Flow Direction	Co-current Flow
Shear Stress	6.3 Pa
Startup Time	4PM, 10/03/2003
Duration	4 days

Table 3 - Test Conditions for Test Wax2003-050

Parameter	Value
Oil Temperature	105ºF
Oil Flow Rate	127 BPD
Oil Velocity	3.9 ft/sec
Oil Reynolds Number	2575
Glycol Temperature	75ºF
Glycol Flow Rate	1600 BPD
Facility	0.5-in. Diameter Test Section
Flow Direction	Co-current Flow
Shear Stress	7.5 Pa
Startup Time	9:30AM, 10/09/2003
Duration	2 days

Table 4 - Test Conditions for Test Wax2003-051

Parameter	Value
Oil Temperature	105ºF
Oil Flow Rate	110 BPD
Oil Velocity	3.3 ft/sec
Oil Reynolds Number	2200
Glycol Temperature	75ºF
Glycol Flow Rate	1600 BPD
Facility	0.5-in. Diameter Test Section
Flow Direction	Co-current Flow
Shear Stress	5.5 Pa
Startup Time	10AM, 10/16/2003
Duration	4.5 days

Table 5 - Test Conditions for Test Wax2003-052

Parameter	Value
Oil Temperature	105ºF
Oil Flow Rate	333 BPD
Oil Velocity	3.6 ft/sec
Oil Reynolds Number	4003
Glycol Temperature	75ºF
Glycol Flow Rate	1600 BPD
Facility	1.0-in. Diameter Test Section
Flow Direction	Co-current Flow
Shear Stress	5.5 Pa
Startup Time	8AM, 10/23/2003
Duration	3 days

Same Fluid Velocity Tests

Tests Wax2003-050, Wax2003-049 and Wax2003-010 were used for this analysis. The test conditions for these tests are summarized in Table 1 and results are presented in Figs. 1 and 2. Figure 1 shows that the actual deposit thicknesses are very similar for the three tests. The dimensionless thickness values, defined as the ratio of the deposit thickness to the inside pipe diameter of the test section (δ/d), are shown in Fig. 2. It can be observed that the dimensionless thickness increases with decreasing pipe diameter. Since the shear stress can be considered constant (varying between 5.5 and 7.5 Pa), this behavior can be attributed to the Reynolds number increasing significantly from 2575 to 6300, covering flow regimes of transition between laminar and turbulent flow and turbulent flow.

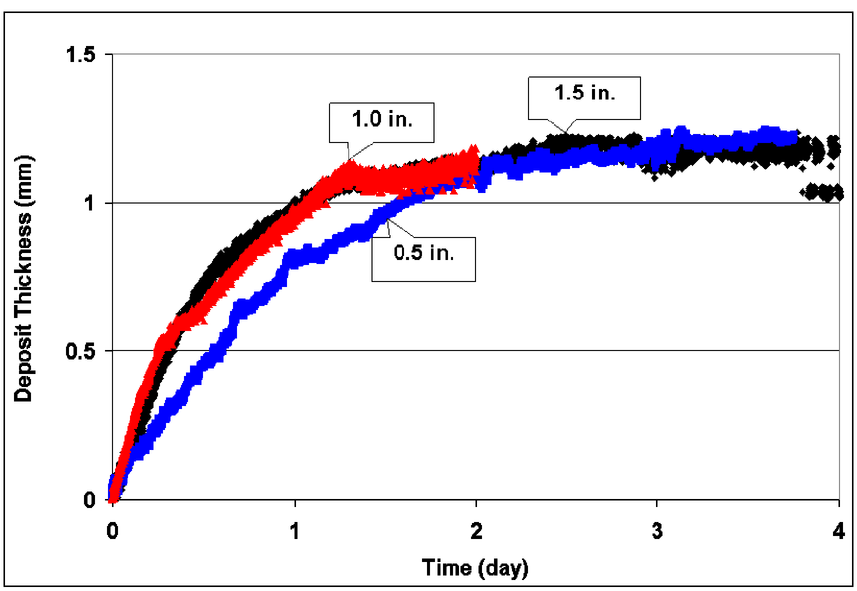

Figure 1 - Comparison of Tests with Same Oil Velocity

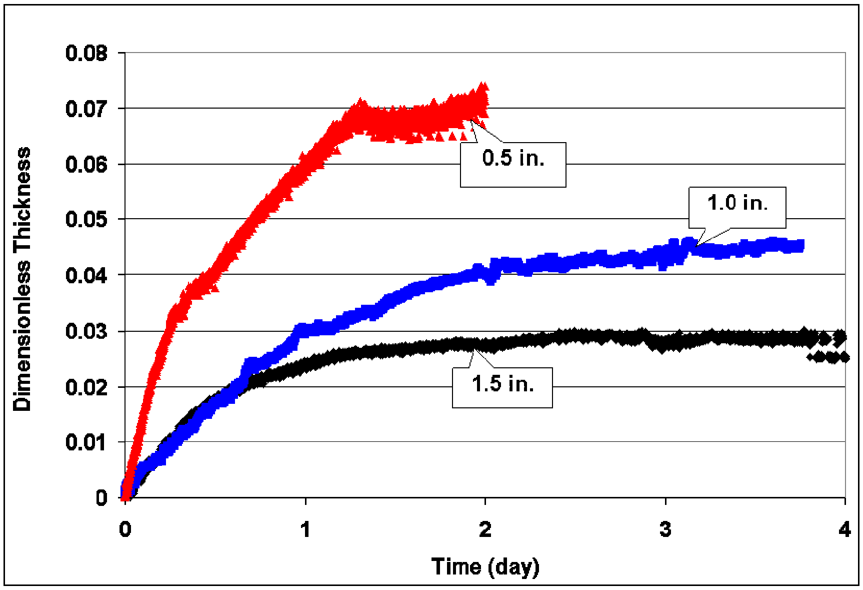

Figure 2 - Comparison of the Tests with Same Oil Velocity (Dimensionless Thickness, δ/d)

Same Shear Stress Tests

A base case was chosen to compare the effect of shear stress. The oil pump can deliver a maximum stable flow rate of 850 BPD. Using this flow rate in the 1.5-in. diameter test section gives the lowest shear stress among the three test sections, 5.5 Pa (Table 1). This shear stress was chosen as the base case. Tests 2003-051 and 2003-052 were conducted with this shear stress in the 0.5-in. and 1.0-in. test sections, respectively. Results of these tests are described below.

Test 2003-051

The test conditions are shown in Table 4. The deposit thickness values calculated using the DP measurements are shown in Fig. 3. After 3 days, deposit thickness reached about 1.7 mm. The TUWAX predictions are also shown in Fig. 3. For the first half day, TUWAX predicted the thickness calculated from pressure drop data very well, and over predicted afterwards. DSC analysis showed that the wax content of the deposit was 39% at shutdown. This was essentially a laminar flow test and resulted in the similar thick and soft deposit observed in previous tests in the Single Phase Loop.

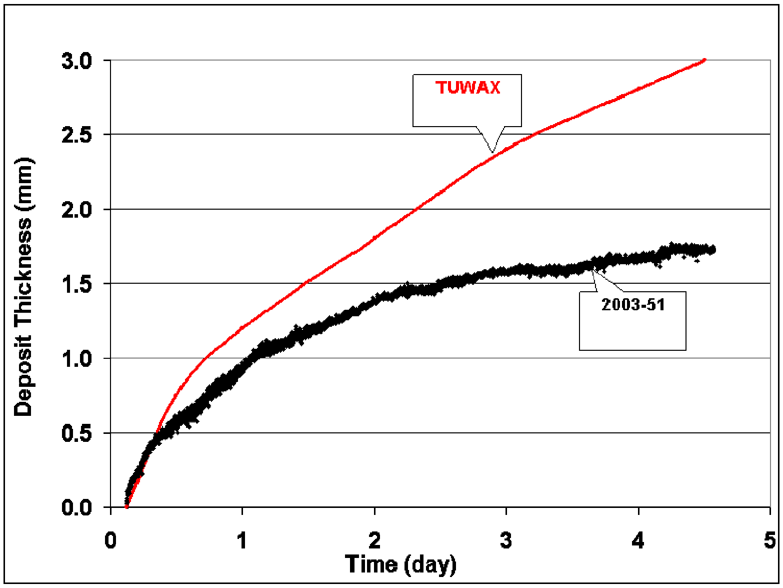

Figure 3 - Deposit Thickness versus Time for Test 2003-051

Test 2003-052

The test conditions are shown in Table 5. The deposit thickness values calculated using the DP measurements are shown in Fig. 4. After 3 days, the deposit thickness reached about 1.4 mm. The TUWAX predictions are also shown in Fig. 4. During the first half day, TUWAX predicted the thickness values calculated from pressure drop data very well, and over predicted afterwards. DSC analysis showed that the wax content of the deposit was 66% at shutdown.

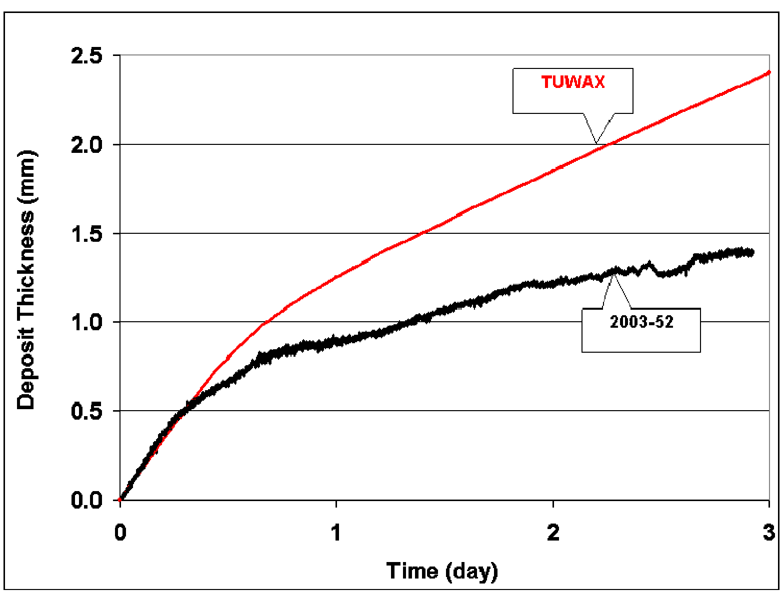

Figure 4 - Deposit Thickness versus Time for Test 2003-052

Analysis of Same Shear Stress Tests

Tests 2003-051, 2003-052 and the earlier test 2003-010 for the 1.5-in. test section were used for this analysis. The test conditions for these tests are summarized in Table 1 and results are presented in Figs. 5 and 6. The deposit thickness versus time shown in Fig. 5 indicates that the thicknesses are very similar for the three cases. Figure 6 shows that the dimensionless thickness increases as the pipe diameter decreases. This behavior can be mostly attributed to the variation in the Reynolds numbers (2200, 4000 and 6300 for 0.5, 1.0 and 1.5-in. pipes, respectively) since the oil velocities do not vary significantly.

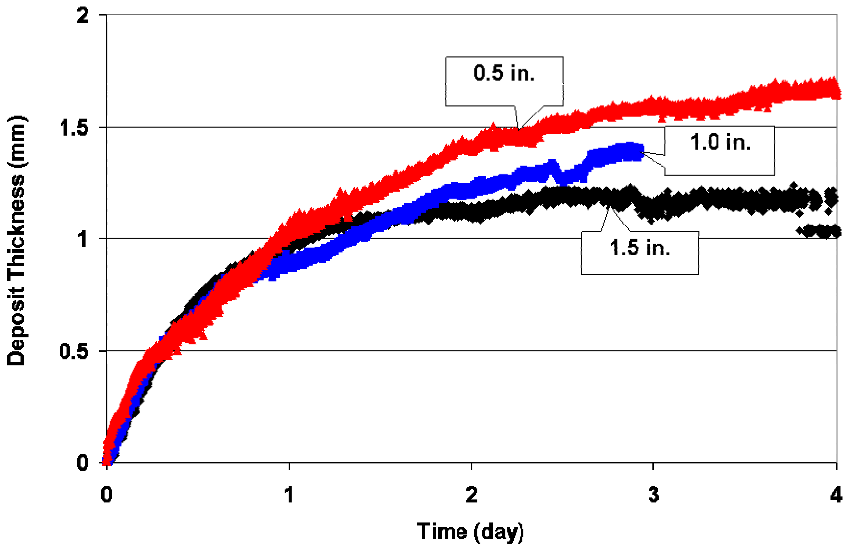

Figure 5 - Comparison of Tests with Same Shear Stress

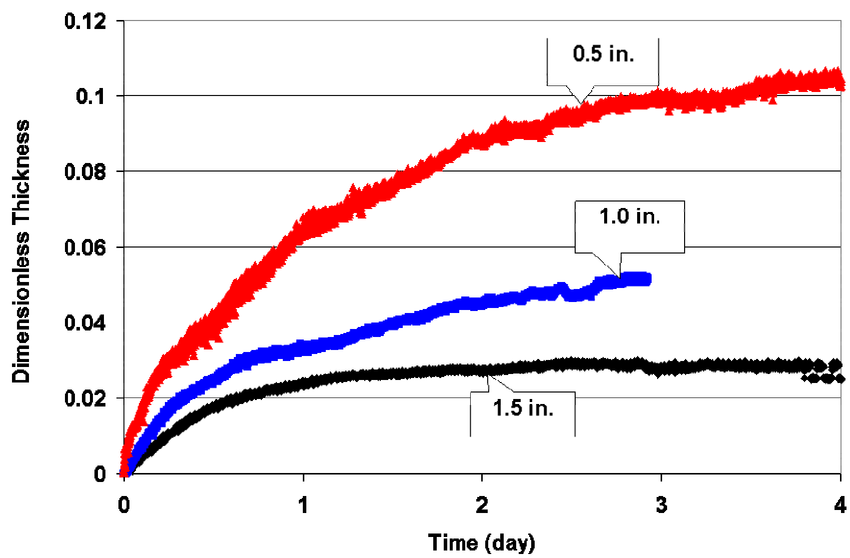

Figure 6 - Comparison of the Tests with Same Shear Stress
(Dimensionless Thickness = δ/d)

Future Work

The focus of tests with the Small Scale Loop during the next quarter will be the first long term test with CBI oil. The purpose of this test is to investigate the aging phenomenon in the film or gel layer that was observed in the Single Phase Loop. The wax content of the deposit has never been observed to be above 20%. The hope is to generate a harder deposit after a long-term run. If this long-term test with CBI oil produces a harder deposit, a similar test could be conducted with Caratinga oil.

Single Phase Loop Studies

After the Fall Advisory Board meeting, the CBI oil was transferred out of the Single Phase Loop. The loop was cleaned with three batches of kerosene and left to dry for about a week. Ten barrels of Caratinga oil from Petrobras were loaded into the flow loop for testing.

Caratinga Fluid Properties

Caratinga oil has two DSC peaks. TUPDP DSC results reported a first peak at 116°F (47°C) and a second peak at 66°F (19°C) (Fig. 7). Petrobras results reported a first peak point at 122.64°F (50.36°C) and a second peak at 66.5°F (19.17°C) (Fig. 8). Differences can be attributed to the different cooling rates. Petrobras tests used a 0.2°C/min cooling rate while TUPDP tests used 2°C/min.

The total wax fraction as a weight percentage from Fig. 9 is seen to be 3.85. Solubility curves for both Caratinga oil and CBI oil are presented in Fig. 9. Similarities in the cumulative wax percentages of both Caratinga oil and CBI oil are evident.

The variation of Caratinga oil viscosity with temperature was determined experimentally by Petrobras. The correlation given by Eq. 1 was developed to predict the viscosity as a function of temperature, where μ represents Caratinga oil viscosity (cP) and T is the temperature of the oil (°K).

$$\log(\log(\mu + 0.7)) = 9.8342 - 3.8375\log(T) \qquad \text{Eq. 1}$$

A comparison between the measured and the correlated viscosity values is shown in Fig. 10.

Due to the viscosity range (from 13 cP to 700 cP for temperatures between 175°F and 40°F), the discharge pressure of the oil pump for Caratinga oil will be much higher than observed during CBI oil tests. Experimentally, flow rates up to 700 BPD can be achieved with oil temperatures around 70°F (laminar cases) due to pressure limitations in the system.

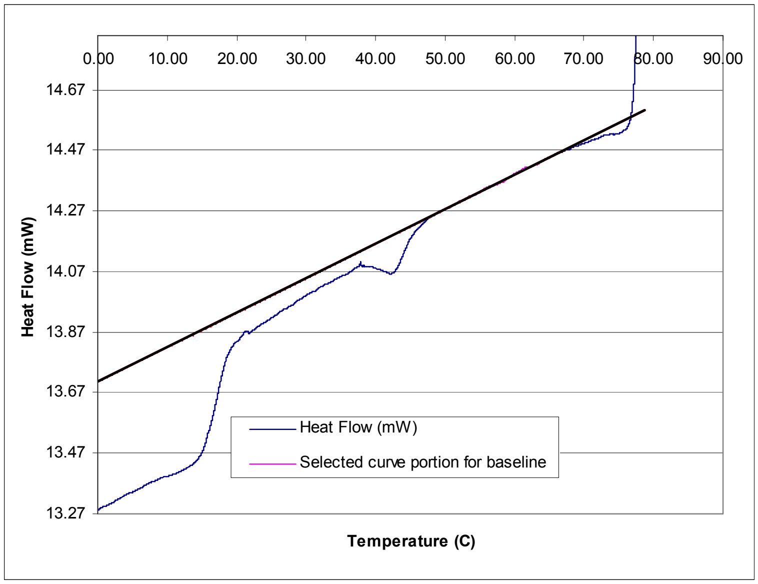

Figure 7 - Heat Flow Chart and Baseline for Caratinga Oil. (TUPDP)

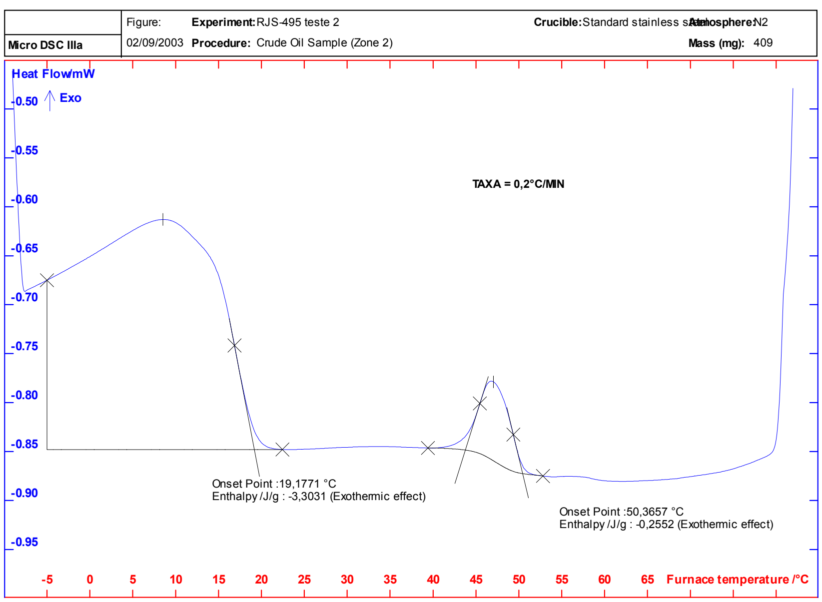

Figure 8 - Heat Flow Chart and Baseline for Caratinga Oil. (Petrobras)

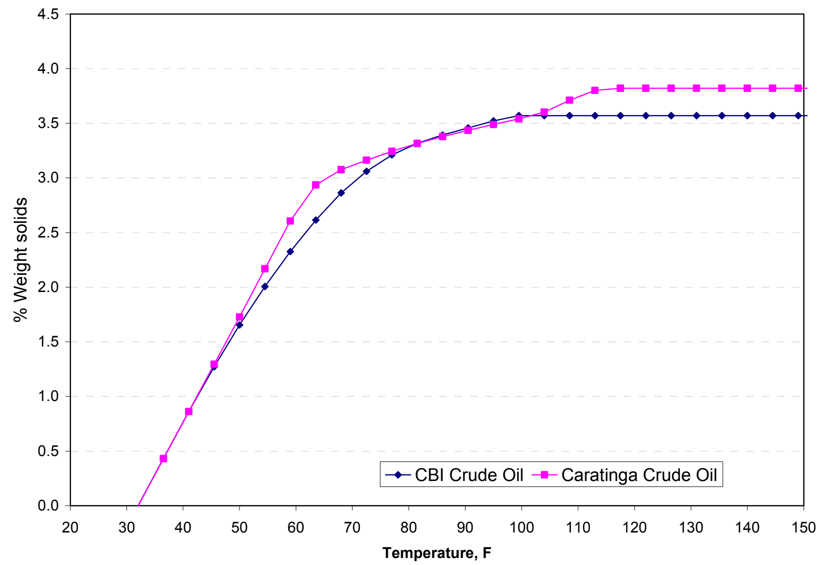

Figure 9 - Cumulative Wax Percentage for Caratinga and CBI Oils

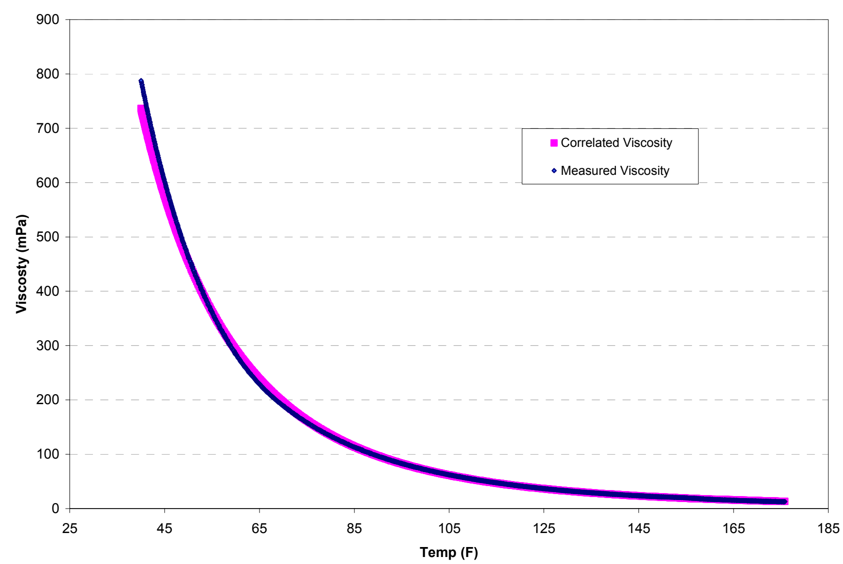

Figure 10 - Comparison between Correlated and Measured Viscosity for Caratinga Oil

Test Matrix for Caratinga Oil

As mentioned previously, analyses of DSC results for the Caratinga oil showed two peaks on the DSC trace, one small peak at about 50°C and a larger one at around 19°C. Field data indicate that deposition is occurring in the pipe region operating below 20°C. The four deposition tests shown in Table 6 were completed during this quarter.

Table 6 - Test Matrix for Caratinga Oil

Test	Oil inlet Temp (F)	ΔT (F)	Flow Rate (BPD)
1 WAX2003-055	122	30	500
2 WAX2003-056	95	30	500
3 WAX2003-057	70	30	500
4 WAX2003-058	70	15	500

Test Results

No significant deposits were formed in any of the tests in Table 6. Test 3 showed a thin layer of a gelled oil or deposit, but this film was beyond the measurement accuracy of our instruments. No changes in pressure drop or temperature profiles were observed for any of the tests. DSC tests are being run on the small deposit from Test 3 to quantify its nature. Summary observations for each test are provided in Appendix A.

Future Work

Simulations are planned to compare predictions with other oils and field data in order to understand why small or no deposits were formed in our tests, while significant amounts of wax were retrieved in the field. Some of the field data for the modeling effort is presented in Fig. 11. Additional data, such as HTGC analysis and another DSC analysis will be obtained. A longer term test (96 hours) below the second peak is also planned. It is speculated that the high viscosity of the fluid (about 4 times that of CBI) is why we are seeing very low deposition rates. The viscosity of the oil will be measured again to obtain more current viscosity data of the oil loaded in the flow loop.

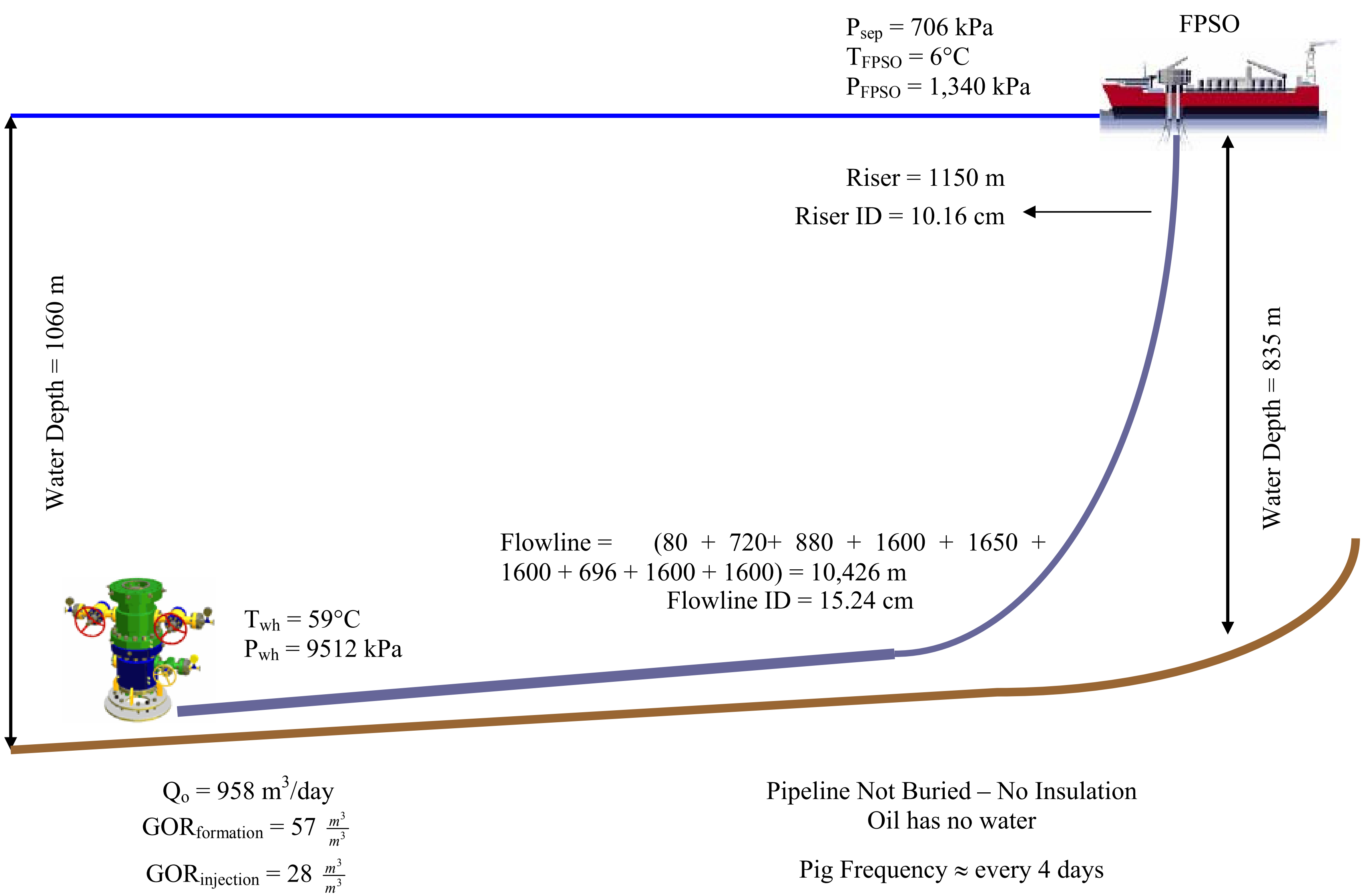

Figure 11 – Data for Caratinga Production Facilities

Two-Phase Loop Studies

Two additional tests were conducted with the Garden Banks condensate to investigate the effect of high oil superficial velocities on deposit thicknesses for vertical flow. The test conditions involved flowing Tulsa City natural gas and Garden Banks condensate in the test section at horizontal and vertical positions for up to 24 hrs. The inlet oil-gas mixture temperature was 85°F for both tests and the inlet glycol-water mixture temperature was 43°F (ΔT of 42°F) for both tests. The system was under a pressure of 350 psig during testing. The glycol-water mixture flow rate was maintained at 2,000 BPD in both tests. Table 7 summarizes the completed tests.

Table 7 - Summary of Garden Banks Condensate Additional Tests

Test Number	V_{sl} (ft/s)	V_{sg} (ft/s)	Angle	Flow Pattern	Start-up Procedure	ΔT (ºF)
WAX2003-047	1.0	4.0	Vertical	Intermittent	New Procedure	42
WAX2003-048	2.0	1.0	Vertical	Intermittent	New Procedure	42

Results

Previous vertical two-phase flow tests had indicated that, if superficial oil velocities are higher than 1 ft/s, deposit thicknesses become smaller, regardless of the value of gas superficial velocity. The flow rates for these two new tests were chosen based on the original vertical test matrix. Test WAX2003-047 had the same gas superficial velocity of 4 ft/s as test WAX2003-007, but had an oil velocity of 1 ft/s. Test WAX2003-048 had the same gas superficial velocity of 1 ft/s as WAX2003-006, but had an oil velocity of 2 ft/s. Intermittent flow was observed in both tests.

Test WAX2003-047

Test WAX2003-047 was conducted to study the effect of high oil flow rates on the paraffin deposition process under intermittent flow conditions. The superficial oil and gas velocities were 1.0 ft/s and 4.0 ft/s, respectively. The deposit thickness values from offline and online LD-LD measurements were 1.0 mm and 0.9 mm, respectively.

After inspecting the removable spool piece, a light brown, medium-hard wax deposit was found. There were several small gas bubbles in the deposit, which were uniformly distributed (axially and radially) on the spool piece pipe wall. The oil content in the wax deposit was 49% in the spool piece and 53 % in the test section pipe.

The thermal conductivity of wax was assumed to be both equal to and 1.5 times the oil thermal conductivity ($k_{wax}=k_{oil}$ and $k_{wax}=1.5k_{oil}$) in the wax thickness calculations from the temperature data. The overall thickness results from the temperature data using the 1.5 times factor was in good agreement with online LD-LD results (Fig. 12).

Discontinuities in predicted wax thickness after 18 hrs were probably caused by a slight change in the oil flow rate. For the first 18 hrs, the oil superficial velocity was around 1.0 ft/s but then decreased to 0.9 ft/s.

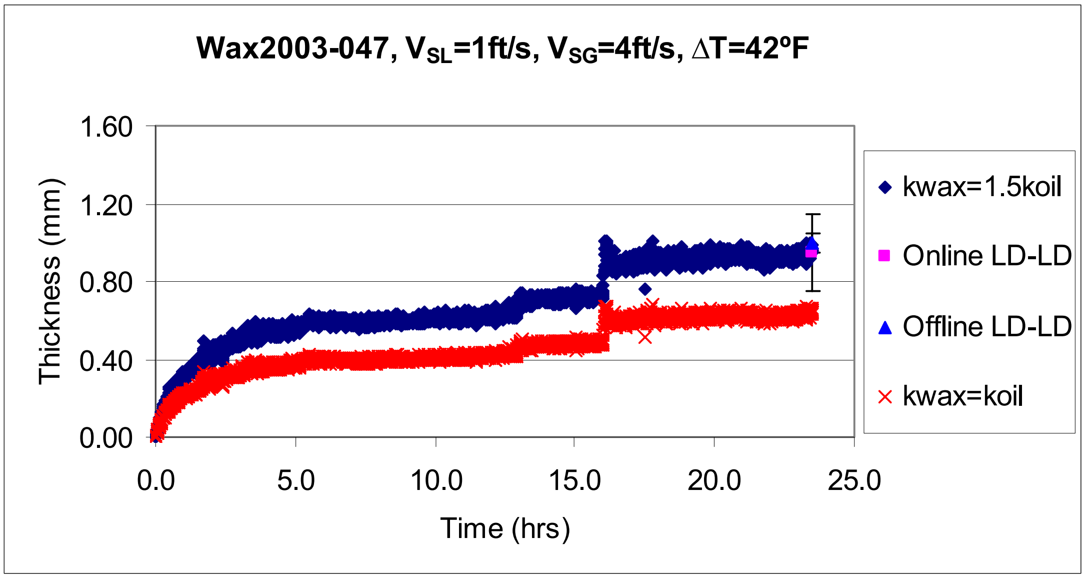

Figure 12 - Average Wax Thicknesses for WAX2003-047

Test WAX2003-048

Test WAX2003-048 was an intermittent vertical flow test with superficial oil and gas velocities of 2.0 ft/s and 1 ft/s, respectively. The deposit thicknesses were 0.6 mm and 0.7 mm from online LD-LD and offline LD-LD measurements, respectively.

From inspection of the spool piece, a medium-hard, light brown deposit uniformly distributed on the pipe surface was observed. Oil content in the wax deposits from the spool piece and the pipe were 50% and 52%, respectively. The wax thicknesses were calculated from the temperature data using thermal conductivity multipliers of 1.0 and 2.0 (k_{wax}=k_{oil} and k_{wax}=2k_{oil}) (Fig. 13).

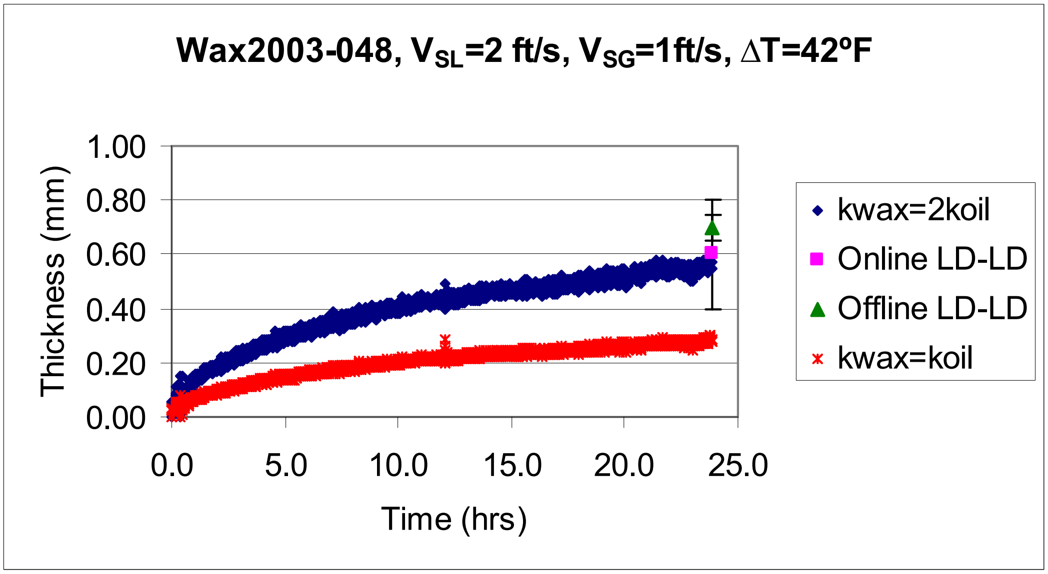

Figure 13 – Average Wax Thicknesses for WAX2003-048

Comparisons

The results of the high oil velocity tests verified that deposit thicknesses become thinner if superficial oil velocity is increased for the vertical flow cases.

Test WAX2003-047 with a superficial oil velocity of 1 ft/s and a superficial gas velocity of 4 ft/s produced results that were expected. The thickness was around 1 mm, which was less than that for the test with same superficial gas velocity but a superficial oil velocity of 0.5 ft/s (WAX2003-006 produced a deposit thicknesses of 1.1 mm and 1.9 mm from online and offline LD-LD measurements, respectively). Moreover, WAX2003-047 yielded thicker deposits when compared with tests WAX2002-014 and WAX2003-023 that had a superficial oil velocity of 2 ft/s and a superficial gas velocity of 3 ft/s (WAX2002-014 produced deposit thicknesses of 0.3 mm and 0.5 mm from online and offline LD-LD measurements, respectively and WAX2003-023 produced a deposit thickness of 0.6 mm from offline LD-LD measurement).

The other high oil velocity test (WAX2003-048) was at the transition boundary between bubbly flow and intermittent flow. The produced thickness was around 0.7 mm for superficial oil and gas velocities of 2 ft/s and 1 ft/s, respectively. The thicknesses were slightly higher than those obtained from bubbly and intermittent vertical tests with a superficial oil velocity of 4 ft/s and 2 ft/s, respectively.

Three-Phase Loop Facility Construction

Modification of the Two-Phase Loop to a Three-Phase Loop is nearing completion. Several tests are planned during the latter part of the 1^{st} quarter, weather permitting.

Cold Finger Experiments

Cold finger experiments to investigate wax deposition with oil-water emulsions continued during the quarter. South Pelto oil has been successfully tested with different water cuts using both fresh water and brine. The first tests were 24 hours long, with the emulsion being created at a mixing speed of 600 rpm. Shorter term tests were then run in order to check for depletion. Based on the results obtained, the 24-hour tests were re-run with a new time period of 6 hours. A different mixing speed of 2000 rpm was also tested in order to create a more stable emulsion and to verify how the mixing speed affects the deposition process. Cold finger tests with CBI oil will be conducted next.

Results

Table 8 shows the results obtained for tests with South Pelto oil. Emulsions were created at a rotational speed of 600 rpm. Three different temperature differences between the bulk oil and the cold finger probes were tested: 15°F, 30°F and 45°F. Tests 2003-CF-026 and 2003-CF-027 are the shorter term tests that confirmed depletion occurred in the 24-hour tests. DSC analyses on the oil and deposit are in progress.

Table 9 shows the results for tests with South Pelto oil where the emulsions were created at a rotational speed of 2000 rpm. The tests were six hours in duration with a temperature difference between the bulk and the probes of 30°F. Test 2003-CF-036 had to be repeated since one of the cells (60% water cut) stopped rotating during the test.

Table 10 shows the tests with the same conditions, but with a mixing speed of 600 rpm. Test 2003-CF-067 had to be repeated due to the same problem as for Test 2003-CF-036.

Results from Tables 8-10 are compared in Figs. 14 and 15.

Table 8 – Cold Finger Tests with South Pelto Oil at Different ΔTs

Test #	Type of Water	WC	rpm	Hrs	ΔT	Av. Weight
013	-	0	-	24	30	2.9 ± 0.5
014	-	0	-	24	15	1.2 ± 0.4
015	-	0	-	24	30	3.2 ± 0.7
016	-	0	-	24	45	5.4 ± 0.2
017	Salt	20	600	24	15	0.8 ± 0.1
	Salt	40	600	24	15	0.6 ± 0.3
018	Salt	60	600	24	15	0.36 ± 0.7
	Salt	80	600	24	15	0.28 ± 0.15
019	Salt	20	600	24	30	1.75 ± 0.15
	Salt	40	600	24	30	1.2 ± 0.1
020	Salt	60	600	24	30	0.66 ± 0.1
	Salt	80	600	24	30	0.56
021	Salt	60	600	24	45	1.38
	Salt	80	600	24	45	0.85 ± 0.1
022	Salt	20	600	24	45	2.3 ± 0.1
	Salt	40	600	24	45	1.3 ± 0.2
023	Fresh	60	600	24	45	0.94 ± 0.15
	Fresh	80	600	24	45	0.67
025	Salt	60	600	24	30	0.91 ± 0.03
	Salt	80	600	24	30	0.46 ± 0.05
026	-	0	-	6	30	1.3 ± 0.15
	-	0	-	3	30	0.74
	-	0	-	1	30	0.83
027	-	0	-	6	45	2.2 ± 0.3
	-	0	-	3	45	1.62
	-	0	-	1	45	1.13
028	Fresh	60	600	24	30	0.83
	Fresh	80	600	24	30	0.44
029	Fresh	20	600	24	30	1.5 ± 0.2
	Fresh	40	600	24	30	1.16 ± 0.02
031(026)	-	0	-	6	30	1.3 ± 0.15

Table 9 – Cold Finger Tests with South Pelto Oil - Mixing Speed of 2000 rpm

Test #	Type of Water	WC	rpm	Hrs	ΔT	Av. Weight
035	Salt	20	2000	6	30	1.21 ± 0.1
	Salt	40	2000	6	30	1.05 ± 0.05
036	Salt	60	2000	6	30	1.16 ± 0.1
	Salt	80	2000	6	30	0.52 ± 0.26
036-Re	Salt	60	2000	6	30	0.78 ± 0.03
	Salt	80	2000	6	30	0.54 ± 0.1
049	-	0	-	6	30	1.37 ± 0.15
053	Fresh	20	2000	6	30	1.1 ± 0.1
	Fresh	40	2000	6	30	0.67 ± 0.1
054	Fresh	60	2000	6	30	0.55 ± 0.1
	Fresh	80	2000	6	30	0.28 ± 0.1

Table 10 – Cold Finger Tests with South Pelto Oil - Mixing Speed of 600 rpm

Test #	Type of Water	WC	rpm	Hrs	ΔT	Av. Weight
066	Salt	20	600	6	30	1.3 ± 0.01
	Salt	40	600	6	30	1.02 ± 0.01
067	Salt	60	600	6	30	-
	Salt	80	600	6	30	0.36 ± 0.04
067-Re	Salt	60	600	6	30	0.83
	Salt	80	600	6	30	0.7 ± 0.06
068	Fresh	20	600	6	30	1.2 ± 0.02
	Fresh	40	600	6	30	0.8 ± 0.03
069 - Re	Fresh	60	600	6	30	0.59 ± 0.05
	Fresh	80	600	6	30	0.55 ± 0.02

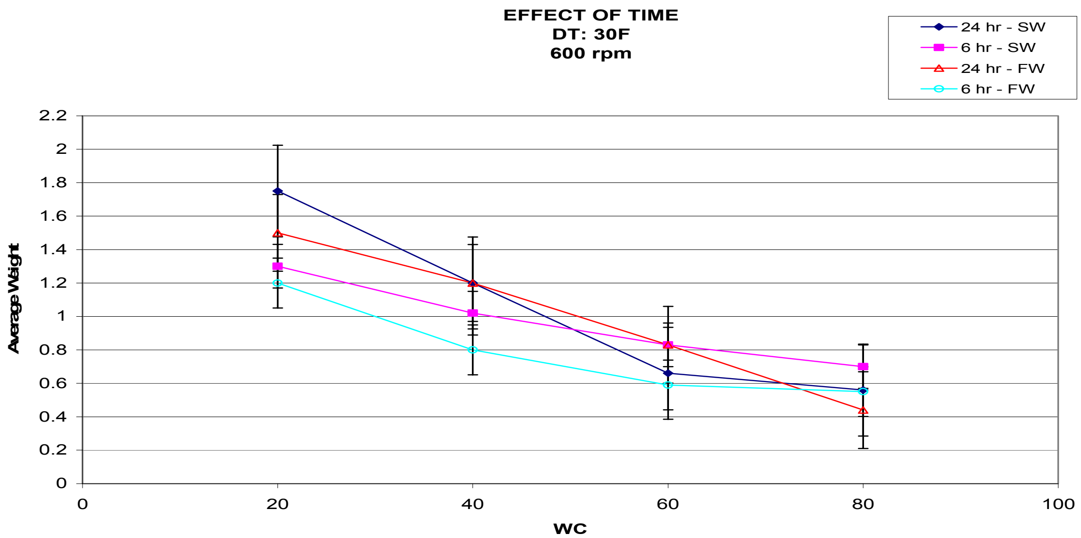

Figure 14 – Effect of Time and Salinity on Deposition for South Pelto Oil

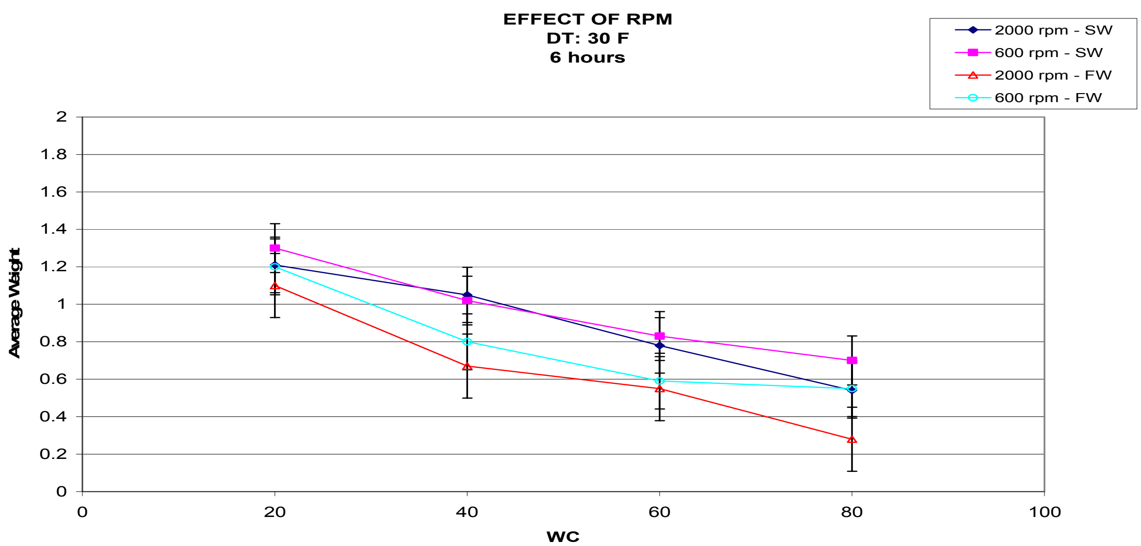

Figure 15 – Effect of Rotational Speed and Salinity on Deposition for South Pelto Oil

Conclusions

- For all conditions, the amount of deposit decreases with an increase in water cut. Following are possible explanations:
  - The lower amount of oil with higher water cuts may be a cause for the lower amount of deposit.
  - The higher heat capacity of the water may increase the wall temperature of the beaker, reducing the driving force for wax deposition.

    - The presence of water molecules weakens the wax structure, enhancing any sloughing effect due to the continuous rotation of the cells. This could reduce the wax deposition as water cut increases (Hsu, J. J. C. and Santamaria, M. M., “Wax Deposition of Waxy Live Crude Under Turbulent Flow Conditions”, SPE 28480, 1994).

- Essentially all deposition takes place within the first 6 hours of testing (about 80% of the deposit), with a mixing speed of 600 rpm, with either salt water or fresh water.

- For the mixing speeds tested, 600 rpm and 2000 rpm, water salinity does not have a large effect on the wax deposition results obtained.

Future Work

The first part of the cold finger tests, which involves South Pelto oil and a ΔT of 30°F, is complete. The second and third parts, with ΔTs of 15°F and 45°F, respectively, are ongoing and are expected to be concluded by the third week of February.

The next step is to test CBI oil for the same conditions as the South Pelto tests. The expected completion date for these tests is around the second week of March.

Modeling Updates for TUWAX

The mechanistic two-phase flow heat transfer model developed by Manabe was incorporated into the TUWAX program. The previous OSU heat transfer model is still available as an option. Figure 16 shows that the Manabe mechanistic heat transfer model performed quite well in predicting two-phase flow heat transfer.

Viscosity tuning capability was added to the TUWAX multiphase flow program. The method for tuning viscosity is the same as for the single-phase program.

After some numerical testing and GUI revisions by MSI, a new version of the TUWAX program will soon be released to TUPDP member companies.

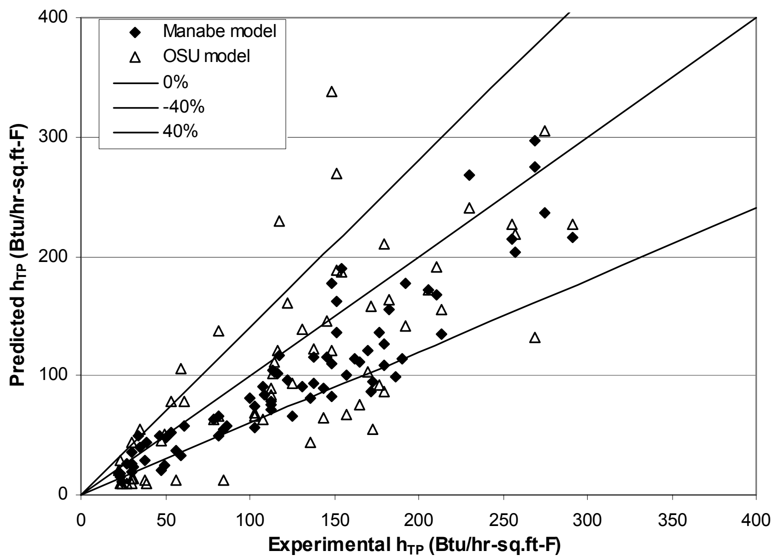

Figure 16 - Comparison of Manabe Model and OSU Model with Experimental Data

Revised Scope of Work

An ad hoc Committee meeting was held December 2, 2003 in Houston to obtain additional input and/or comments from participants. In attendance were Baker Petrolite – David Jennings; BP – Taras Makogon; Champion Technologies – Tom Williams; ChevronTexaco – Jeff Creek and Rama Venkatesan (Jack Hsu via conference call); ConocoPhillips – Probjot Singh via conference call; ExxonMobil – Scott Hickman; Nalco – Steven Allenson and Olga Lindeman; Shell – George Broze and Tulsa University – Cem Sarica and Mike Volk. These comments were used to refine the Scope of Work and task charts that are provided in Appendix B. These charts will now be utilized by the Committee in the development of the detailed work plan for each task.

Advisory Board Information

Plans have now been finalized for the Spring 2004 Advisory Board meetings. The TUHFP Advisory Board meeting will be held from 8:00 a.m. – 3:00 p.m. on March 30, 2004. This meeting is scheduled to be held in the Gallery Room of the Allen Chapman Activity Center (ACAC) on the Main Campus of The University of Tulsa. A tour of the test facilities will be held on Tuesday, March 30 at 3:00 p.m. Following the tour, there will be a joint TUFFP/TUPDP BBQ between 5:00 - 7:00 p.m. The TUFFP Advisory Board meeting will be held at the Renaissance Tulsa Hotel and Convention Center. The meeting will begin at 8:30 a.m. on Wednesday, March 31 and will adjourn at 5:00 p.m. Following the TUFFP meeting, there will be a joint TUFFP/TUPDP reception from 6:00—9:00 p.m. at the Renaissance. The TUPDP Advisory Board meeting will be held on April 1 at the Renaissance. The meeting will begin at 8:00 a.m. and will adjourn at 5:00 p.m. The Request for Information form and hotel information will soon be placed on the web page. All persons from your company that plan to attend the Advisory Board meetings, should complete and return these forms as soon as possible to help us plan the meetings. Information on the Advisory Board meetings can also be found on our web site at www.tufpc.org/tuffp/abminfo.asp. You can then follow the links for the Request for Information form. TUFFP Advisory Board meeting brochures will be available for members at the meeting and a concerted effort will again be made to have the combined brochure and slide copy available for downloading from the web site at www.tufpc.org/tuffp/abm_brochures.asp shortly before the meeting. The brochure will contain sufficient information to help each attendee actively participate in discussions on current and future research projects, financial matters, and operating procedures.

Appendix A – Caratinga Test Results

Test 1

The objective of this test was to study paraffin deposition phenomena near the first DSC peak (116°F (47°C)). Due to the oil and glycol inlet temperatures, the viscosity of the oil varied over a range of 40-80 cP.

Figure A1 shows the oil temperature profile in the test section during the steady state period. The oil outlet temperature remained constant, indicating zero deposit build up. Figure A2 shows the pressure drops per segment and the overall measurement (line on top). A constant pressure drop was measured for each segment, as well as overall, again indicating that no deposition was taking place inside the pipe.

LD-LD results for Test 1 are summarized in Table A1. Considerably lower values for deposit thickness were measured when compared with the results for the previous oils (CBI oil, South Pelto oil and Garden Banks condensate). Most of the measurements were within the uncertainty range of the device.

From visual inspection, a uniform-black-thin gel was observed on the pipe wall. Analyses of DSC tests for the oil and wax samples are not yet available.

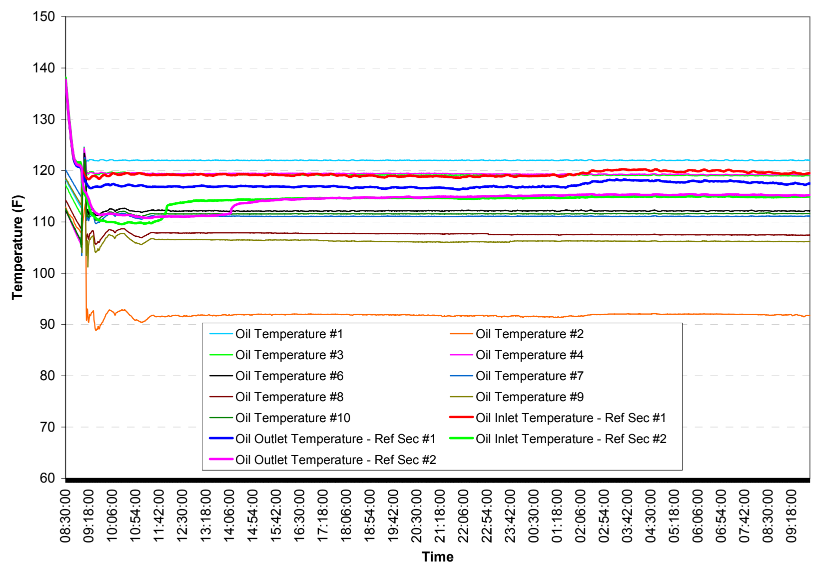

Figure A1 - Oil Temperatures in Test 1

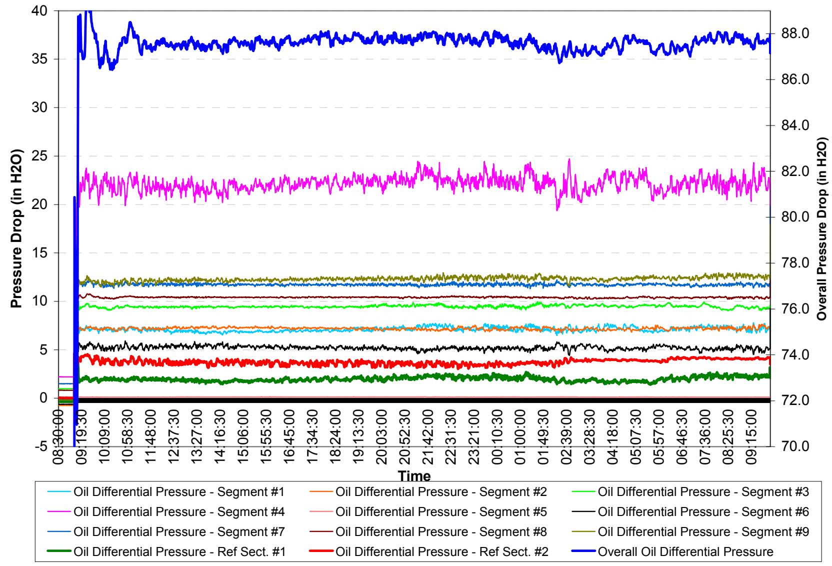

Figure A2 - Pressure Drops in Test 1

Table A1 - LD-LD Results for Test 1

	Measurement 1 (mm)	Measurement 2 (mm)	Average (mm)
Spool Piece 1	0.05	0.06	0.055
Spool Piece 2	0.17	0.06	0.115

Test 2

The objective of this test was to study paraffin deposition phenomena in the temperature range between the DSC peaks. Viscosities between 35cP and 225cP were expected for the oil based on the oil inlet and glycol temperatures.

The same behavior as in Test 1 was observed during Test 2. Oil outlet temperatures and pressure drops remained constant during the testing period. Figures A3 and A4 show the oil temperature and pressure drop profiles, respectively. A black-uniform-thin layer was observed on the pipe wall when the spool pieces were removed. The layer was soft and very similar to the oil. Results from the DSC analyses are not yet available.

LD-LD results are summarized in Table A2. Small thicknesses of the deposit within the uncertainty range of the device were measured.

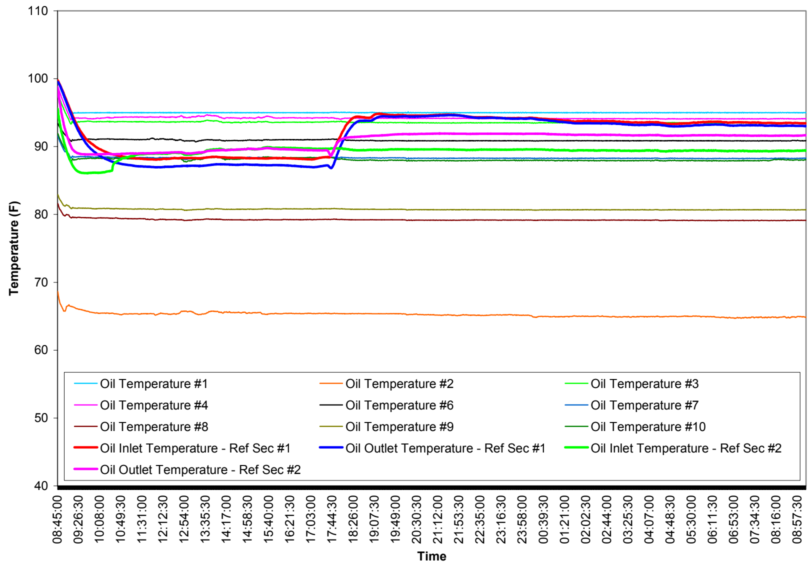

Figure A3 - Oil Temperatures for Test 2

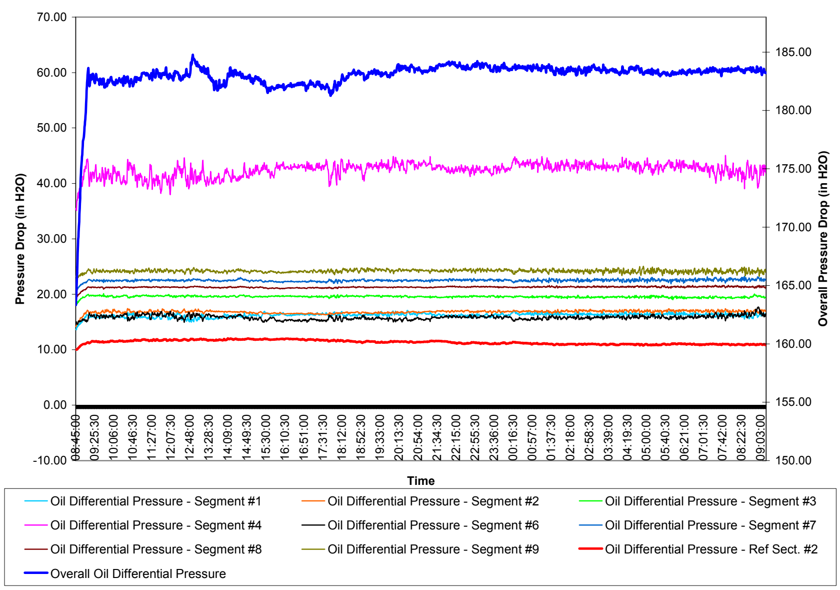

Figure A4 - Pressure Drops for Test 2

Table A2 - LD-LD Results for Test 2

	Measurement 1 (mm)	Measurement 2 (mm)	Average (mm)
Spool Piece 1	0.12	0.15	0.135
Spool Piece 2	0.02	0.02	0.020

Test 3

The objective of this test was to study paraffin deposition phenomena near the second DSC peak. Due to the temperature range of the oil (between the oil inlet temperature and the glycol temperature), oil viscosities between 189 cP and 740 cP were expected.

Figures A5 and A6 show the oil temperature and pressure drop profiles inside the test section during the steady state period. The outlet temperature remained stable through the entire testing period, indicating no deposition inside the test section. However, a slight increase of 10-in. H_2O was observed in the overall pressure drop.

Visual inspection of the spool pieces showed a soft, thin oil layer on the pipe wall. LD-LD measurements in both spool pieces indicate a deposit thickness less than 0.3 mm. The results are summarized in Table A3. DSC analyses are still in progress for the oil and wax samples.

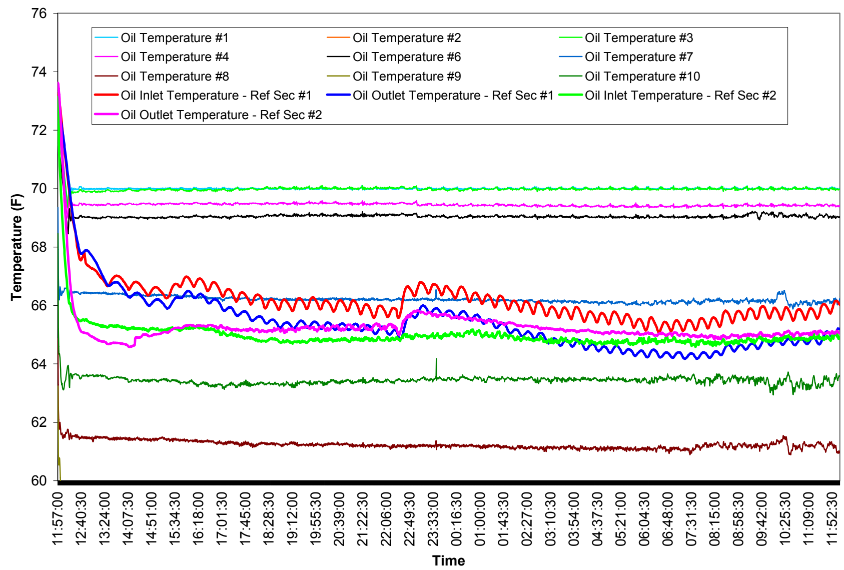

Figure A5 - Oil Temperatures for Test 3

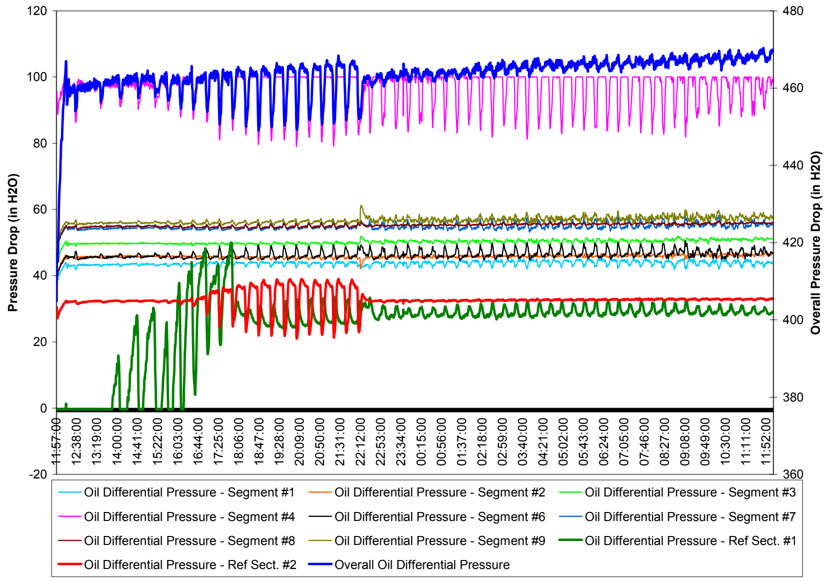

Figure A6 - Oil Pressure Drop Measurements for Test 3

Table A3 - LD-LD Results for Test 3

	Measurement 1 (mm)	Measurement 2 (mm)	Measurement 3 (mm)	Measurement 4 (mm)	Average (mm)
Spool Piece 1	0.21	0.21	0.52	0.23	0.293
Spool Piece 2	0.12	0.12	0.17	---	0.137

Test 4

The objective of this test was to study paraffin deposition phenomena near the second DSC peak using a smaller ΔT. A smaller ΔT results in lower oil viscosities since the wall temperature is higher. The decrease in oil viscosity may aid the paraffin deposition process since it improves the diffusion in the liquid phase. Due to the temperature range of the oil (between the oil inlet temperature and the glycol temperature), viscosities between 189 cP and 360 cP were expected.

Figures A7 and A8 show the oil temperature and pressure drop profiles in the test section, respectively. As in Tests 1 and 2, the oil outlet temperature and pressure drop remained fairly constant throughout the steady state period, an indication of no deposition inside the pipe. LD-LD results are shown in Table A4. Again, deposit thickness values around 0.2 mm were measured, which is within the uncertainty range of the device.

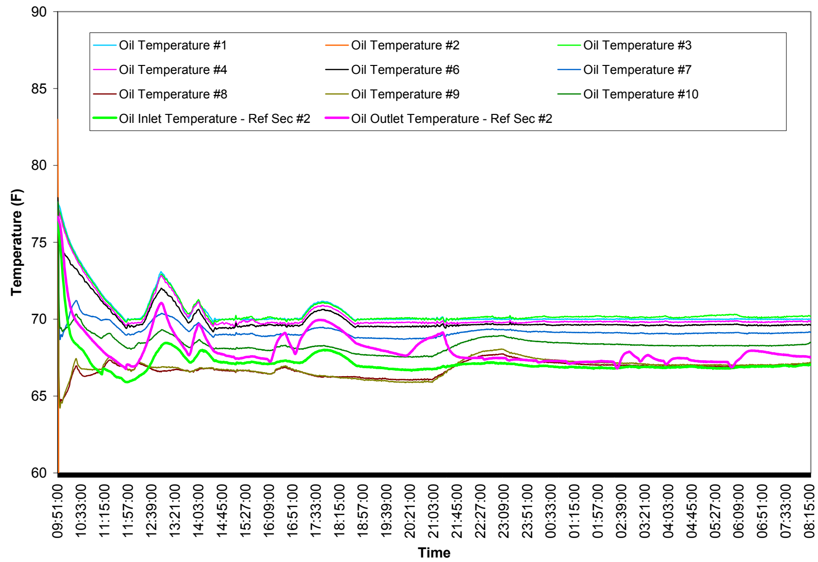

Figure A7 - Oil Temperatures for Test 4

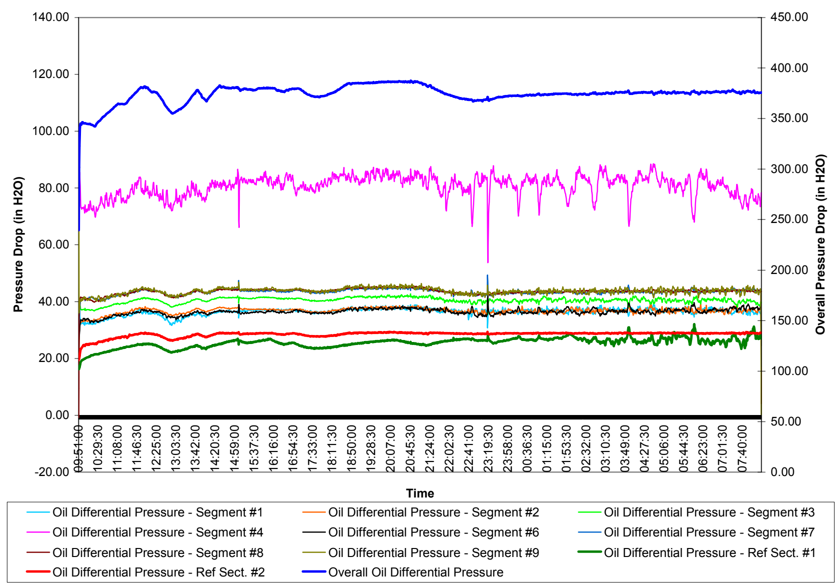

Figure A8 - Oil Pressure Drops for Test 4

Table A4 - LD-LD Results for Test 4

	Measurement 1 (mm)	Measurement 2 (mm)	Measurement 3 (mm)	Measurement 4 (mm)	Average (mm)
Spool Piece 1	0.21	0.21	0.52	0.23	0.29
Spool Piece 2	0.12	0.12	0.17	---	0.13

Appendix B – Scope of Work (3rd Draft)

THE UNIVERSITY of TULSA

College of Engineering and Natural Sciences
Tulsa University Paraffin Deposition Projects

Project 1 Single Phase Studies

Task 1: Review of Available Models: The literature will be reviewed for available new models. Several are known to exist, such as those developed P. Singh and R. Venkatesan.

Task 2: The models identified in Task 1 will be coded and incorporated into TU's single phase model and evaluated against in-house data. The following phenomena will be coded and tested.

- Viscosity and density effects on transport
- Scaling factors for inhibitors
- Shear effects
- Insulation effects
- Method to tune WAT
- Depletion effects
- Aging effects
- Gel layer
- Compositional effects

Task 3: TUWAX will be recoded using excel and visual basic. Access to source code will be provided to participants via the web site. The code will be thoroughly documented with comment cards for ease of understanding.

Task 4: Development of an Enhanced State of the Art Single Phase Model – Based on the findings in Task 2, the excel/visual basic model as well as the MSI version will be enhanced to include the suitable models from Task 2 to develop the Enhanced Model.

Task 5: Conduct experiments to enhance single phase model – Several areas will be studied; the impact of shear, gelling and aging.

- Impact of Shear - Examination of the South Pelto crude oil and Garden Banks condensate single-phase data has confirmed that shear stress has an effect on the deposition rate. The deposition rate decreases with an increase in shear stress at the deposit interface. Studies will be conducted in a Haake based or similar type of device such as those manufactured by Brookfield, Rheologica, and Rheometrics.
- Improvements of Deposition Model to Include Such Effects as Gelling and Aging. Experimental studies will be conducted to investigate the gelling and aging processes under different conditions, such as temperature gradient, shear, and fluid composition. ***The gelling experiments are contingent on the findings from Task 2.*** The Small-Scale and Single-Phase Flow Loops will be used in the experimental part of this study. A model capable of handling the gelling phenomena occurring at the pipe wall will be taken from past studies or developed using conservation of mass and momentum and heat transfer. This model will be incorporated in the Enhanced Single Phase Model.
- Haake type experiments or measurements with an in-line viscometer will be made to study rheological effects.

Task 6: The findings from task 5 will be incorporated into the single phase model.

Task 7: Documentation for the software will be provided. This will include on-line help as well as a software users manual.

Project II – Multiphase Studies

Task 1: Two-Phase Deposition Model Enhancements and Developments

Task 1a: Two-phase deposition model enhancements – Improvements in the single-phase model will be incorporated in the multiphase flow model and comparisons with the existing data will be made. Two phase flow paraffin deposition is affected by the hydrodynamics of the two-phase flow; therefore, attempts will be made to further improve the two-phase flow model.

Task 1b: Oil water Studies: Scoping tests were conducted during the previous phase of study using South Pelto crude oil. These tests showed that deposition increased with increasing water cut, contrary to what was observed with the "cold-finger" tests. Additional tests are planned. The small scale loop will be used to conduct oil water studies at different water cuts. These studies will also begin using model fluids followed by real oils.

Task 1c: Tests will be performed using model fluids and salt water to gain an understanding of the rheology. Studies of the effect of inversion and independently measured viscosity of the oil water mixtures will be conducted. A controlled stress Rheometer will be used. This will potentially give us better information than the current "cold finger" tests since we have a better understanding of the shear field and can vary the gap between the "bob" and wall to examine separated flow versus laminar flow in heavy oils.

Task 1d: The findings will be incorporated into the excel/visual basic deposition model. The model performance will be tested against the PDP database.

Task 2 – Three-Phase Model Developments

Gas-oil-water Studies -TUFFP is currently investigating three-phase gas-oil-water flow for low pressure and model fluids (mineral oil, tap water and air) in a 2-in. ID. 130-ft long TUFFP flow loop. TUPDP is also investigating three-phase gas-oil water flow, but for high pressures and with reservoir fluids. Collaboration between these projects will enhance both efforts. The following efforts will be conducted:

Task 2a: A preliminary low pressure three-phase flow mechanistic model will be developed through collaboration with TUFFP. The low pressure three-phase mechanistic flow model will be incorporated into the two-phase model.

Task 2b: Gas-oil-water flow characterization tests at elevated pressures will be conducted using TUPDP's Multiphase Flow Loop. This data, along with the low pressure data, will be used in the model development. The findings will be incorporated into the three-phase model.

Task 2c: The three phase model will be tested against preliminary data from the Phase II studies.

Task 2d: Immediately after completion of the high pressure flow characterization tests, gas-oil-water paraffin deposition experiments will be conducted using the Multiphase Flow Loop.

Task 2e: An attempt will be made to develop a model to predict paraffin deposition during three-phase gas-oil-water flow.

Task 3 – Software Improvements

Task 3a: TUFFP has developed a unified heat transfer model for gas-liquid pipe flow that can be used for all inclination angles from -90^o to 90^o from horizontal, and it gives better predictions than the Manabe mechanistic model. This heat transfer model is consistent with the unified hydrodynamic model for gas-liquid pipe flow and will be incorporated into the excel/visual basic model.

Task 3b: The single phase improvements developed during the first year of study will be incorporated into the two-phase model. The improvements will be tested against the TUPDP data base.

Task 3c: The model enhancements developed in project 2 will be incorporated.

Project 3 – Pigging Studies

Pigging is widely employed as a paraffin remediation method. Since production loss is unavoidable during a pigging operation, optimization of the operation is imperative. This optimization must consider deposition characteristics and performance of the pigs used. While several studies investigating deposition characteristics have either been completed or are currently underway, very few studies have been conducted on the mechanics of wax removal.

Task 1: The study will start with a literature search. Papers, such as that by Souze, et. al, are available for review. The results from this study will be documented

Task 2: Feasibility calculations will be made to determine whether these efforts need to be continued.

Task 3: Field data will be gathered and used to verify any model that may be developed. Attempts will be made to get ChevronTexaco's Angola field data, Amerada Hess's Balpate field data, and Petrobras's Caratinga field data. Any others that might be identified will be incorporated.

Task 4: This task, dependent on Task 1, will investigate pigging efficiency during wax removal for various types of pigs and wax deposits, and provide a better understanding of the removal process. The Single-Phase Flow Loop will be used for these studies. The Single-Phase Flow Loop will be equipped for pigging by adding a pig launcher and a pig receiver along with some modifications to the test facility. The testing will begin with model fluids to enable the development of thicker deposits. Once understood, additional tests will be conducted with the in-house black oils and/or condensate.

Task 5: A wax model will be developed that will be used to predict reliable pigging frequencies.

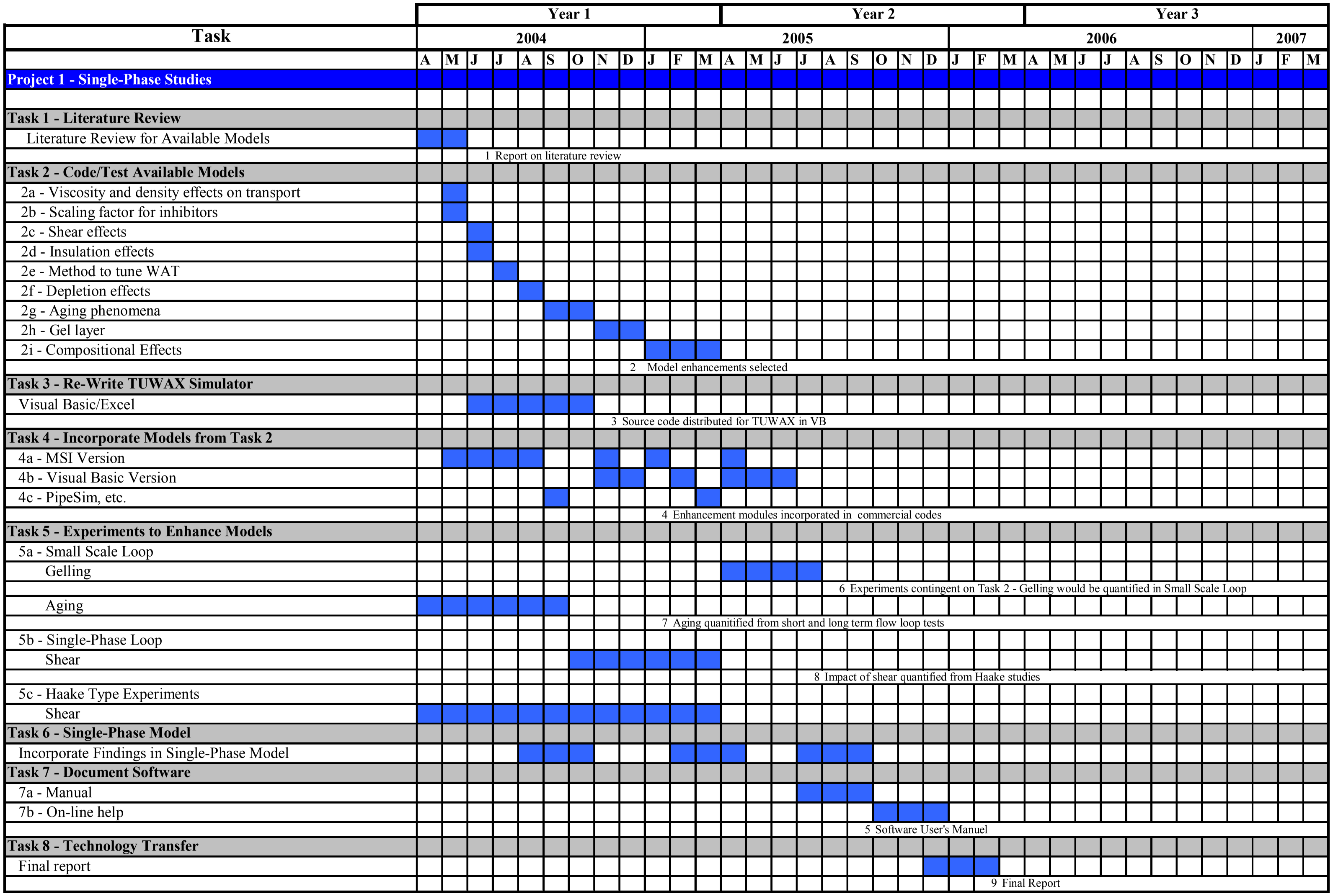

Figure B1 –Single-Phase Studies

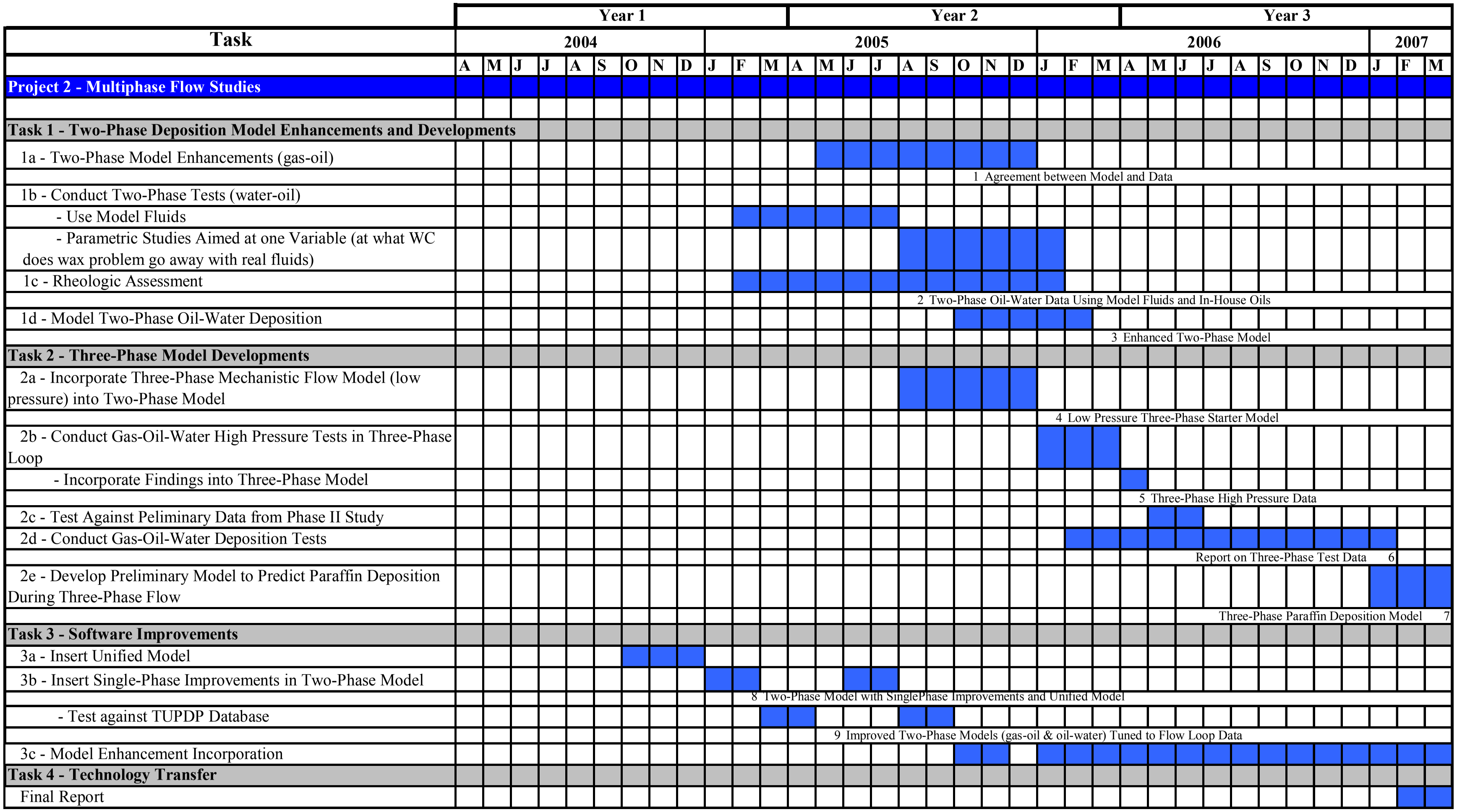

Figure B2 – Multiphase Flow Studies

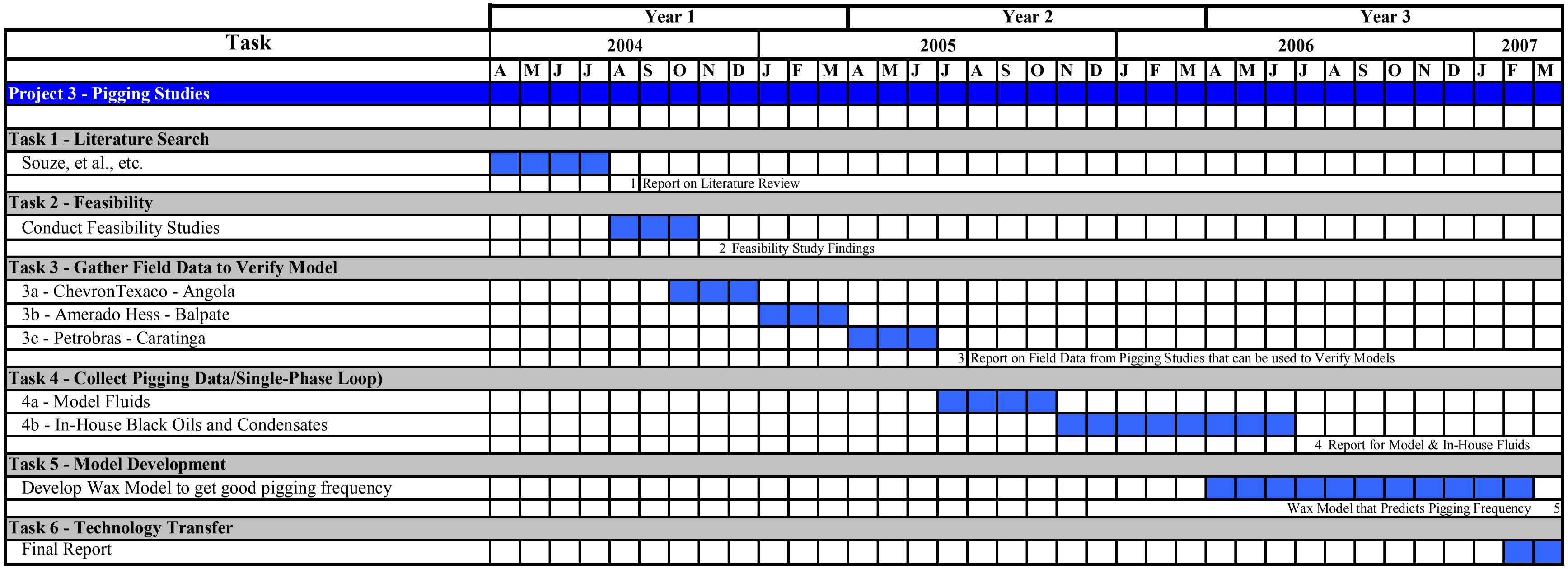

Figure B3 – Pigging Studies