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Tulsa University Paraffin Deposition Projects

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Abstract

As oil and gas production moves to deeper and colder water, subsea multiphase production systems become critical for economic feasibility. It will also become increasingly imperative to adequately identify the conditions for paraffin precipitation and predict paraffin deposition rates to optimize the design and operation of these multiphase production systems. Although several oil companies have paraffin deposition predictive capabilities for single-phase oil flow, these predictive capabilities are not suitable for the multiphase flow conditions encountered in most flowlines and wellbores. For deepwater applications in the Gulf of Mexico, it is likely that multiphase production streams consisting of crude oil, produced water and gas will be transported in a single multiphase pipeline to minimize capital cost and complexity at the mudline. Existing single-phase (crude oil) paraffin deposition predictive tools are clearly inadequate to accurately design these pipelines because they do not account for the second and third phases, namely, produced water and gas.

The objective of this program is to utilize the current test facilities at The University of Tulsa, as well as member company expertise, to accomplish the following: enhance our understanding of paraffin deposition in single and two-phase (gas-oil) flows; conduct focused experiments to better understand various aspects of deposition physics; and, utilize knowledge gained from experimental modeling studies to enhance the computer programs developed in the previous JIP for predicting paraffin deposition in single and two-phase flow environments. These refined computer models will then be tested against field data from member company pipelines.

The following deliverables are scheduled during the first three projects of the program:

1. Single-Phase Studies, with three different black oils, which will yield an enhanced computer code for predicting paraffin deposition in deepwater and surface pipelines.

2. Two-Phase Studies, with a focus on heat transfer and paraffin deposition at various pipe inclinations, which will be used to enhance the paraffin deposition code for gas-liquid flow in pipes.

3. Deposition Physics and Water Impact Studies, which will address the aging process, improve our ability to characterize paraffin deposits and enhance our understanding of the role water plays in paraffin deposition in deepwater pipelines. As in the previous two studies, knowledge gained in this suite of studies will be integrated into a state-of-the-art three-phase paraffin deposition computer program.

Graduate students, post-Doctoral Research Associates and Visiting Scholars will primarily conduct the research in these projects.

Knowledge will be transferred to the industry through semiannual Advisory Board Meetings, graduate education of one Ph.D. student and four M.S. students, and through the coordination of annual workshops for hands on experience using computer programs developed during the research.

Introduction

The frontier for oil and gas exploration and production is deepwater; however, as oil and gas production moves to deeper and colder water, subsea multiphase production systems become critical for economic feasibility. It will also become increasingly imperative to adequately identify the conditions for paraffin precipitation and predict paraffin deposition rates to optimize the design and operation of these multiphase production systems. Accurate information about the potential for, and extent of, wax deposition is very critical, not only towards the operation and design of these systems, but also for assuring their economic feasibility. Although several oil companies have paraffin deposition predictive capabilities for single-phase oil flow, these predictive capabilities are not suitable for the multiphase flow conditions encountered in most flowlines and wellbores. DeepStar was formed to identify and develop the required technology. A $4.5 million JIP to investigate paraffin deposition at The University of Tulsa was formed in May 1995 and is a spin-off from DeepStar.

New petroleum production horizons at water depths greater than 500m have driven industry to develop new technologies for preventing and controlling the deposition of petroleum wax. Traditional methods of management, prevention, and remediation have been established for many years. The greater water depths mean lower temperatures, no fixed platforms (TLP's and FPSO's are expensive) and subsea wellheads. The longer and fewer production lines in deeper water make economic solutions to prevention, management, and remediation key to economic development of these new deepwater resources.

The cost of remediation due to pipeline blockage from paraffin deposition is on the order of $200,000 when the water depth is 100m, but on the order of $1,000,000 when the remediation occurs in water depths near 400m. The cost is proportionately greater as development depth increases.

Since its inception, the petroleum industry has been plagued by paraffin. Its long time nature as a nuisance, easily and inexpensively treated onshore with chemicals and scrappers, has resulted in a lack of basic research regarding the actual deposition phenomena. However, paraffin deposition can be the determining factor for not producing deepwater fields, many of which are tied to nearby platforms with subsea flowlines. These remote facilities at low temperatures are vulnerable to deposition of paraffin in tubulars, which could lead to a potentially expensive, catastrophic event in the history of a project.

This inherent engineering and economic challenge has led to a renewed interest in studying the problem within the petroleum industry. Many oil and gas related companies have studied paraffin deposition and have predictive capabilities for paraffin deposition during single-phase oil flow. However, these predictive capabilities are still unproved and not suitable for multiphase flow conditions encountered in most flowlines and wellbores. It is important to model the deposition rate to optimize pigging schedules, to design appropriate chemical treatments, or to design insulated systems to minimize or alleviate paraffin deposition in wellbores or flowlines.

1. Executive Summary

Twenty companies are currently members of the consortium. These members include: Baker Petrolite, BG International, BHP Billiton Petroleum, BP Exploration, Champion Technologies, ChevronTexaco Exploration and Production Technology Company, Conoco-Phillips, Department of Energy (DOE), ExxonMobil Upstream Research, Japan National Oil Corporation, Marathon Oil Company, Minerals Management Services, ONDEO Nalco Energy Services, ONGC, Pemex, Petrobras, Shell E & P Technology Company, Statoil, TotalFinaElf and Unocal. Three companies will participate as "in-kind" members: Alberta Research Council, Multiphase Solutions, Inc. and PetroCanada.

The facility was modified to eliminate the temperature fluctuations that were seen in prior tests and then repeat tests were conducted. The repeat tests produced wax deposits that were very similar in thickness as to those observed earlier.

Deposition tests in the small scale facility were conducted in the 0.5 and 1-in. test sections at a Reynolds Number of 6300. The 1-in. test section had a deposit that was 0.8-in. thick while the 0.5-in. test section had a deposit that was 0.4-in. thick. It is postulated that the thickness decreased as a result of increasing shear stress, 43 Pa vs. 14 Pa.

A long term test was designed and conducted to study depletion. This test was started with the tank half full and once the thickness plateaued, the tank was filled with another barrel of fluid. After increasing for the first three days, the deposit thickness then stabilized for the next five days. A one barrel oil charge was then added and after 2 days, the deposit thickness began to increase again. This depletion effect was also shown in the 27 day test in that the wax appearance temperature of the oil decreased from 115°F to 89°F while the wax content in the deposit increased from 42% to 67% at the end of the test.

The oil-water feasibility tests were conducted using the South Pelto crude oil for water cuts of 25, 40, and 75% in the 1.5-in. test section at a flow rate of 850 BPD. Although preliminary, these results showed a thicker deposit for the 25% water cut test versus an equivalent single-phase test. When the water cut was increased to 40%, significant abrupt fluctuations were observed in the pressure response as a function of time was observed. Additional studies are needed before drawing any conclusions. In the last test, the water cut was increased to 75%. The deposit thickness generated in this test was equivalent to that generated in the single-phase test: however, the Reynolds number for this test was 550 (laminar flow) because of the increase in viscosity while the single-phase test was 6300 (turbulent flow).

Single-phase tests with the CBI fluid were completed. A total of 15 tests were conducted. Three tests were conducted to study the effect of ΔT. ΔT's of 15, 30 and 45°F were used. Wax thicknesses increased with an increase in ΔT for ΔT's less than 30°F but decreased for the 45°F ΔT because of the change in viscosity that affects the diffusivity factor. The highest wax content was found for the lowest ΔT.

Three single-phase tests were also conducted to study the effect of oil inlet temperature. The same thickness trend was observed. DSC analyses confirmed the hypothesis of higher wax content in the deposits at higher temperatures.

Six single-phase tests were conducted to study the effect of flow rate. In general, wax thickness decreased with an increase in flow rate while the wax content in the deposit increased.

Four single-phase tests were conducted to study the effect of time. These tests showed that wax thickness, as well as wax content, increased with time. The deposits were gels for the short term tests, < 24 hours, but had a consistency of Vaseline after 96 hours.

As reported in the previous report, the CBI fluid has a gel layer that appears to creep. This effect was not seen when South Pelto crude oil was tested. Similar tests will be conducted using Garden Banks and the Caratinga fluid.

Ten repeat multiphase tests using the Garden Banks condensate were completed. Two-phase tests with this fluid are now complete. This fluid will remain in the facility and be used for the upcoming gas-oil-water tests.

Most of the horizontal tests yielded deposits around 0.2 to 0.4 mm. Annular flow tests with oil velocity below 1 ft/s gave deposits around 0.8-1.0 mm. Higher oil velocity in vertical flow resulted in a thinner deposit in annular flow (0.2-0.3mm).

Similarly, vertical intermittent flow tests with oil velocities below 1 ft/s yielded thicker deposits (more than 1 mm). Higher oil velocities (above 1 ft/s) in vertical intermittent flow yielded much thinner deposits similar to those obtained in horizontal flow with oil velocities above 1 ft/s.

The South Pelto oil produced thicker deposits than the Garden Banks condensate with the exception of the vertical intermittent tests. For those tests, the Garden Banks condensate produced a thicker deposit than the South Pelto crude oil. The produced deposits from South Pelto were harder than those of Garden Banks.

South Pelto deposition tests run under similar conditions produced thicker deposits, except for the intermittent vertical flow tests.

The addition of the water system on the multiphase flow loop is still ongoing. All plumbing is now complete and the oil-water separator has been pressure tested. The instruments and instrumentation wires are in place. After completing the transformers upgrade in late August, the water pump is now being hooked-up. Efforts in the coming months will concentrate on connecting the new instruments and controls to the existing acquisition system and modifying the user-interface and control routines to accommodate oil-water-gas tests. This phase will be done after the last two oil-gas tests scheduled with Garden Banks. Commissioning is anticipated shortly thereafter.

Three different types of tests have been conducted using the Cold Finger device since the last Advisory Board Meeting; cold finger commissioning and calibration tests, to verify the operation of the device and repeatability of the results, single-phase tests with a focus on the effect of ΔT, and preliminary oil/water test to investigate the effect of water.

For the single-phase tests, the deposits were all very soft, essentially like a gelled oil. The overall mass of the deposit increased as the ΔT increased, but the average wax fraction decreased.

Four tests with four different water cuts have been run with South Pelto crude oil; two cells running with 20% salt water and two with 40% salt water content. The amount of deposits for both water cuts, especially 40%, are less than the ones verified for single-phase tests at the same ΔT. Visually, the deposits obtained for single-phase test and 20% water cuts are very similar in thickness. For 40% water cuts, the deposits were very thin and not homogeneous around the probe.

Several improvements have been made to the wax deposition software (TUWAX). These improvements include heat transfer calculations in the single-phase and multiphase wax deposition modules.

During the past few months, our web page has undergone a drastic transformation! We think you are going to like the new look and content and hope that you find the website more useful and easier to navigate.

From the front page of the website - you will be able to access both TUFFP and TUPDP websites. From this page you can access all the information regarding TUPDP, background information, publications, calendar, our facilities, and research projects and personnel.

Member company names have now been linked to their respective websites. Links to TU Consortia will be provided along with links to other sites of interest. All users will have a unique login and password - if you haven't been notified of your login and password, please contact Linda Jones at jones@utulsa.edu or (918) 631-5110.

There have been two very significant additions to the web site. There is now a search engine available in the members' area, where you could look for research reports, programs, papers, etc., either by name, keywords, or author. Another addition will be mail lists that you can subscribe to. This will be a great place to come if you have inquiries and want input from other members. The new url is www.tufpc.org. Please let us know how we can further improve the Web site.

The Spring 2004 Advisory Board Meeting will be held on Thursday, April 1st. The location of the meeting has not yet been determined.

2. Experimental

a. Test Fluids

The tests conducted in the flow loops to date have used an oil from Mobil Oil Corporation's South Pelto Oil Field, Well 10E, in the Gulf of Mexico, a condensate from Shell Oil Company's Block 426, Well A-14, Garden Banks condensate in the Gulf of Mexico, and oil from ChevronTexaco's Cote Blanche Island that was stored at the Humble test facility. The South Pelto oil contains approximately 4.11% (based on Nenninger) wax by weight, and has a WAT of approximately 49ºC (120ºF). The density of this 35º API (specific gravity of 0.85) crude oil was measured continuously with a Micro Motion mass flow meter. Appendix 3.1 of the Final Report on Fluid Characterization and Property Evaluation (Creek, et al. 1999) reports measured data on the oil from the South Pelto Field.

The Garden Banks fluid is a 42º API (specific gravity of 0.82) condensate with approximately 1.88% (based on Nenninger) wax by weight. The WAT of the condensate is approximately 43.3ºC (110ºF) as measured using Cross-Polar Microscopy (CPM). Appendix 3.2 of the Final Report on Fluid Characterization and Property Evaluation (Creek et al., 1999) reports measured data on the condensate from Garden Banks 426 Field.

Two additional fluids were required for the study: one for the model validation study and one for the single-phase test program. Another fluid was needed for the single-phase test program since only a few tests could be run with the Garden Banks condensate due to depletion problems.

In November 2001, a decision was made to utilize ChevronTexaco's CBI crude as the third fluid for the single-phase studies. Ten (10) bbls of this fluid were loaded into a TU storage tank in November and then shipped to the University.

Due to the characteristics of the Cote Blanche Island (CBI) crude oil (heavy and more viscous than the previous oils tested), a better understanding of the behavior was necessary. Table 2.1 shows some of the CBI properties (ChevronTexaco data).

Samples were sent to TotalFinaElf and ExxonMobil for DSC and viscosity analyses, respectively. From DSC analysis, the WAT was found to be 99ºF. The new measured viscosity was twice that previously reported by ChevronTexaco. The new viscosity data will be used in all our data processing since the oil was sampled from the facility after it was loaded. Also, from the viscosity analysis (cone and plate rheometer) the oil exhibits a Newtonian behavior for shear stresses of 92 s^{-1} and above; the 3 s^{-1} case shows a shear rate dependency starting at 93 ºF. Figures 2.1 and 2.2 show the results for both analyses.

Figure 2.3 shows the difference between the viscosities measured by ChevronTexaco and ExxonMobil. The ExxonMobil measurement is considered more representative of our oil and therefore will be used. Efforts to seek a third viscosity measurement are underway.

In February 2002, a meeting was held with Petrobras regarding utilizing their Caratinga oil from the Campos Basin as the model validation fluid. This field has a production history that goes from 100% oil to one that produces both oil and water. This oil also has field data (T, P, volume of wax pigged, etc.). The viscosity is higher than CBI's by a factor of 4 and has two wax appearance temperatures (117°F and 63°F) based on DSC measurements. During these discussions, it was decided that the Caratinga oil would be utilized. Samples were taken and arrived in Tulsa in January, 2003. The properties of the fluids being used in the deposition studies are shown in Table 2.2.

Table 2.1 - Cote Blanch Island (CBI) Crude Oil Properties

API Gravity	24
Specific Gravity	0.910
Wax Appearance Temperature [ºF]	105
Pour Point [ºF]	44
C20+ Wax Content %	6.3

Table 2.2 – Fluids Used in Deposition Studies

Property	ExxonMobil	Shell	Texaco	Petrobras
	S. Pelto	Garden Banks	CBI	Caratinga
API, Gravity	35	42	24.0	24.3
WAT, F	120	110	105	Two peaks 117 and 63
Pour Pt, F	60-80		44	0
Wax, wt%	4.11	1.88	6.3	5.4
Viscosity @60, cp	23.5	4.5	48	~110
Viscosity @100, cp	6.8	2.6	15	~40
Asphaltenes			3.4	18
Resins			3.4	27
Water Cut%			?	<1%

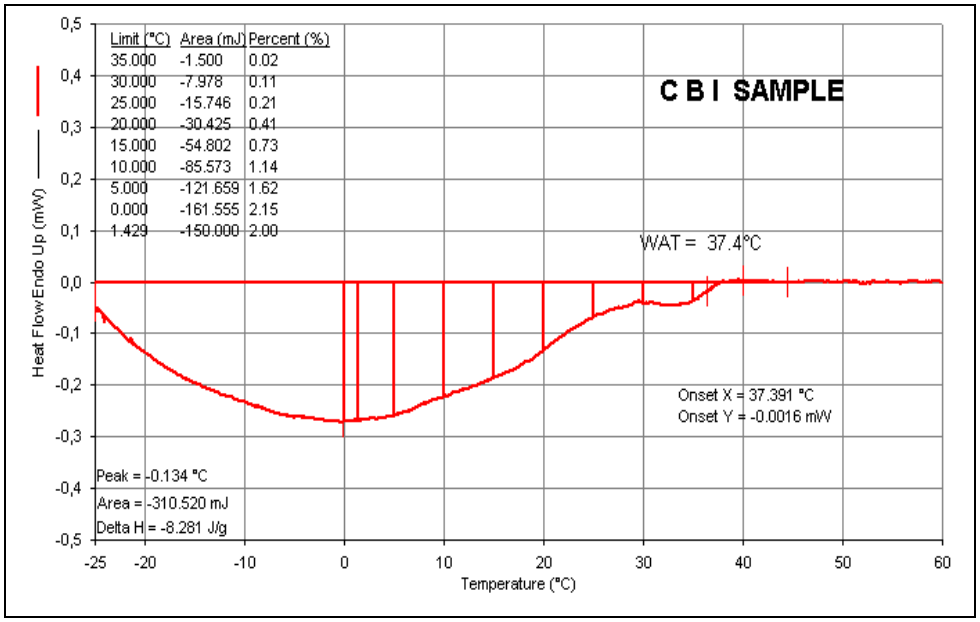


Figure 2.1 - Cote Blanche Island DSC Results from TotalFinaElf

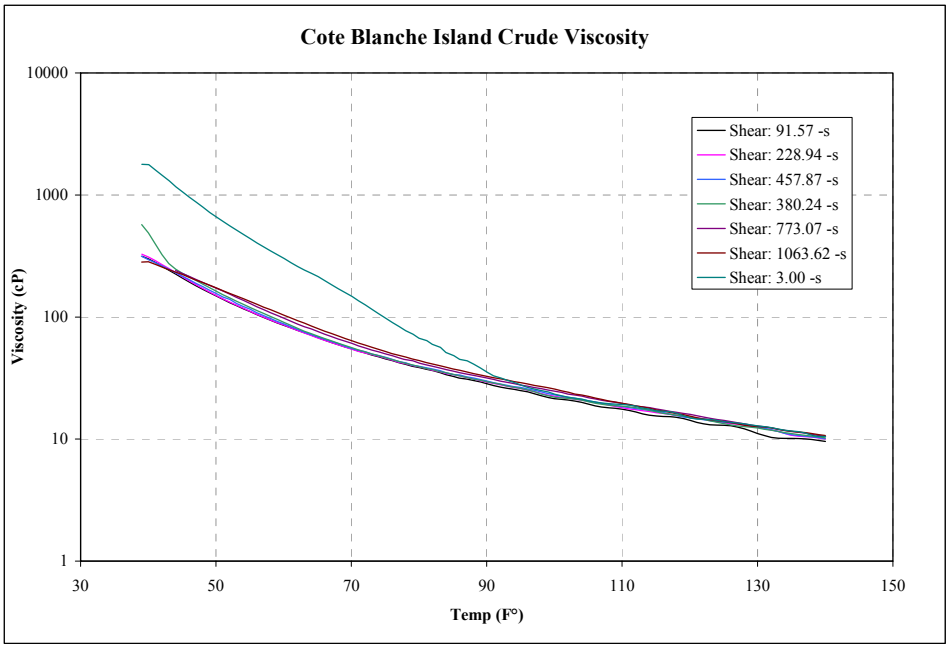


Figure 2.2 - Cote Blanche Island Viscosity Analysis from ExxonMobil

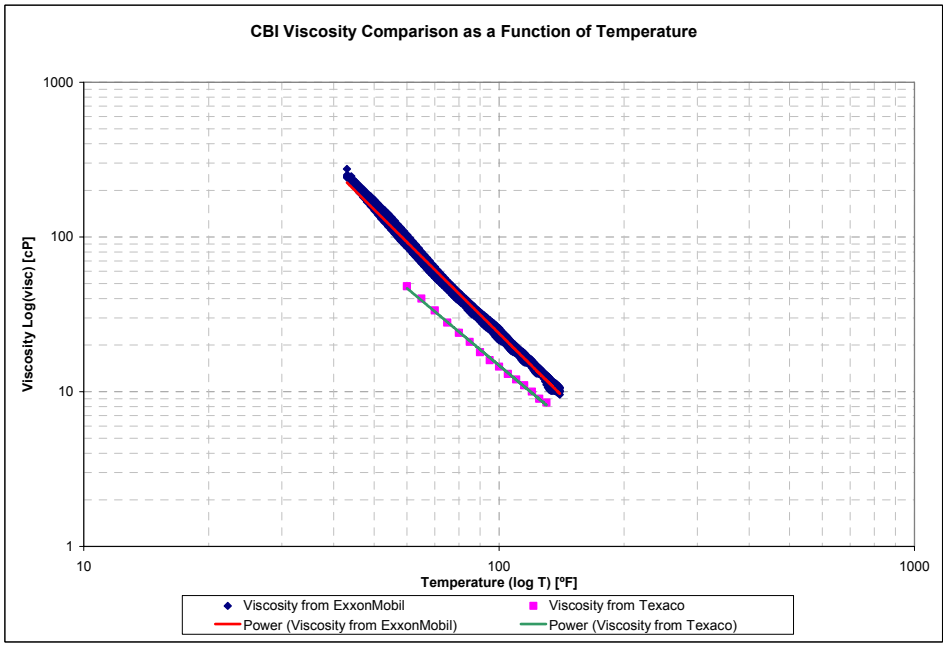


Figure 2.3 - Comparison between ExxonMobil and ChevronTexaco CBI Viscosity Data

b. Small-Scale Loop

i. Facility Description

Currently, there are two large-scale facilities, the Single-Phase Loop and the Multiphase Loop, to handle single-phase paraffin deposition tests and multiphase paraffin deposition tests, respectively. These two facilities are fairly complicated. At least two people are required to operate and monitor the facilities whenever they are running. This is a big obstacle for long-term tests that may last more than one week or even one month.

A new Small-Scale Loop has been constructed to meet the above particular needs. The construction started in March 2002 and was completed in August 2002. The facility includes an oil system, a glycol system and a test section. The oil system is presented in Fig. 2.4.

Oil is stored in a 2-bbl oil tank with a 10-20 psig nitrogen blanket on top. A variable speed mixer keeps the temperature in the tank uniform and maintains homogeneous oil-water dispersions during oil-water experiments. Oil is circulated by a sliding vane pump with a capacity of 900 BPD. Gas boilers and heat exchangers were used for heating in the single-phase and multiphase paraffin deposition flow loops used in earlier studies. In contrast to these two facilities, a 15-kW circulation heater is used in the Small-Scale Loop to heat the oil directly to the desired temperatures. The heater has been designed to output a maximum heat flux of 10-12 W/in.^{2}, in order to avoid high skin temperatures and cracking of the oil. The circulation heater for the Small-Scale Loop simplifies the operation of the facility and reduces the capital and operating costs associated with a complete hot glycol system with a gas boiler. After oil flows through the developing and test sections, its flow rate and density are measured by a micro motion flow meter. The glycol systems are presented in Fig. 2.5.

The design of the glycol system was modeled after the existing Single-Phase and Multiphase Flow Loops of TUPDP. A cold glycol system circulates a 50% water-glycol solution through a tube-shell heat exchanger and into a 10-ton chiller. A three-way control valve facilitates the temperature control. The glycol flow rate is controlled by the bypass control valve using feedback coming from the Micro Motion flow meter. Co-current or countercurrent flow can be achieved in the test section by switching the direction of control valves. Co-current flow has been applied in all the tests for modeling convenience.

The test sections consist of three Schedule-40 steel pipes with the nominal diameters of 0.5 in., 1.0 in. and 1.5 in. to accommodate different ranges of flow rates, as seen in Fig. 2.6.

Glycol is flowed in the annulus between the test pipes and the jackets. 3-in. nominal diameter steel pipes with an inside diameter of 3.826 in. are used as jackets. The jacket sizes have been chosen in order to match glycol velocities and outside heat transfer coefficients with those on the other two facilities.

Each test section is about 110-in. long and is completely welded. A 7-ft long hydraulic section allows development of the flow regime and eliminates the entrance effects prior to entering the jacketed section. The ratio of the test section length to oil tank volume is used as a scaling parameter. This ratio is comparable to the one for the Multiphase Flow Loop and ensures a comparable oil charge for the deposition area to avoid depletion.

The 1.5-in. diameter test section is also equipped with a pig receiver and a pig launcher to perform pigging operations.

Two temperature transducers are used to monitor inlet and outlet oil temperatures. The facility was first commissioned with TT2 installed and connected in front of the developing section to monitor all three test sections. However, the oil outlet temperature was found to oscillate with the ambient temperature. A possible reason was speculated to be the heat loss from the developing section. Therefore, TT2 was modified to monitor the inlet temperature at the beginning of the jacketed section rather than before the developing section. The meter wire is connected through the DP ports at the inlet without moving the

transducer TT2 itself. Detailed information is given in the Facility Modification section.

Each test section is equipped with three different ports that can be opened during and after a test. The sizes of the ports are the same as the diameters of the test sections. These ports are used to sample deposits at different times during a test.

Finally, a three-way valve manifold on the glycol system is used to allow co-current flow as well as counter-current flow.

ii. Description of a Typical Test

Oil is heated to 140°F and keeps circulating overnight to melt the wax deposit from a previous test. It is then allowed to cool naturally to about 120°F. Afterwards, the glycol system is started to cool the oil to test conditions and when the parameters stabilize at test conditions, steady state is achieved. At shutdown, oil is displaced to the oil tank with nitrogen. Samples and pictures can be taken afterwards.

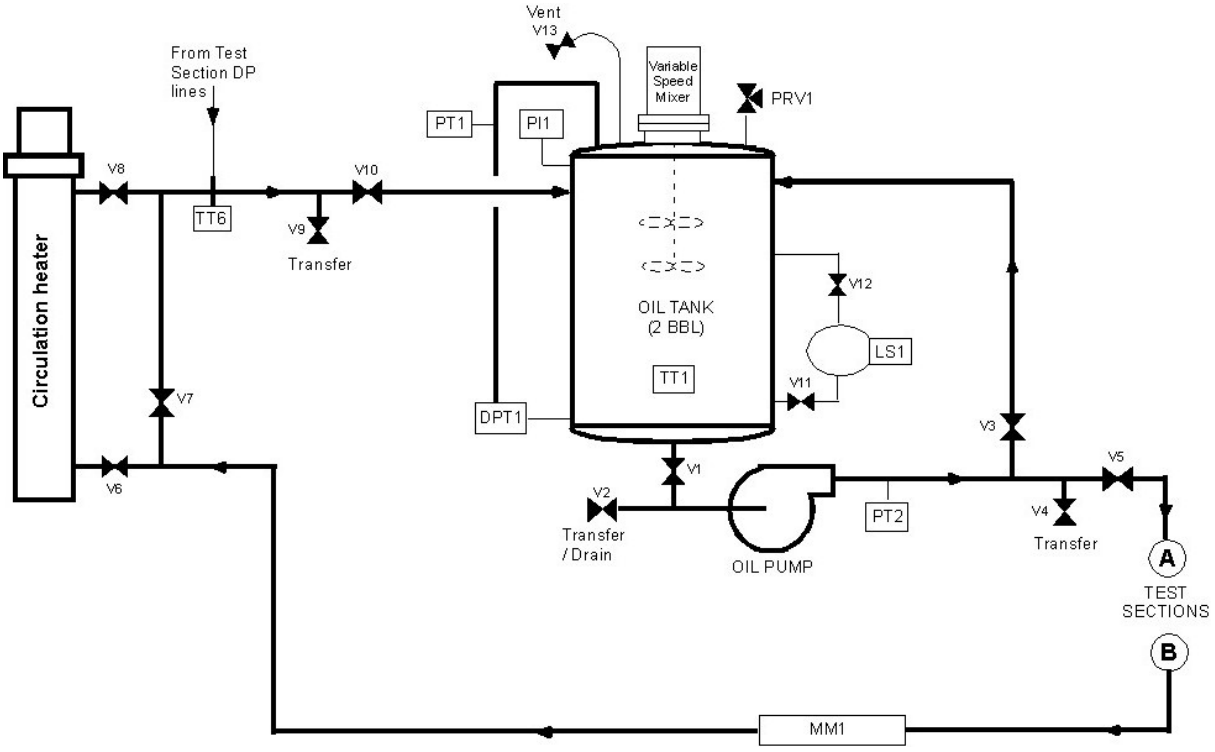


Figure 2.4 - Oil System

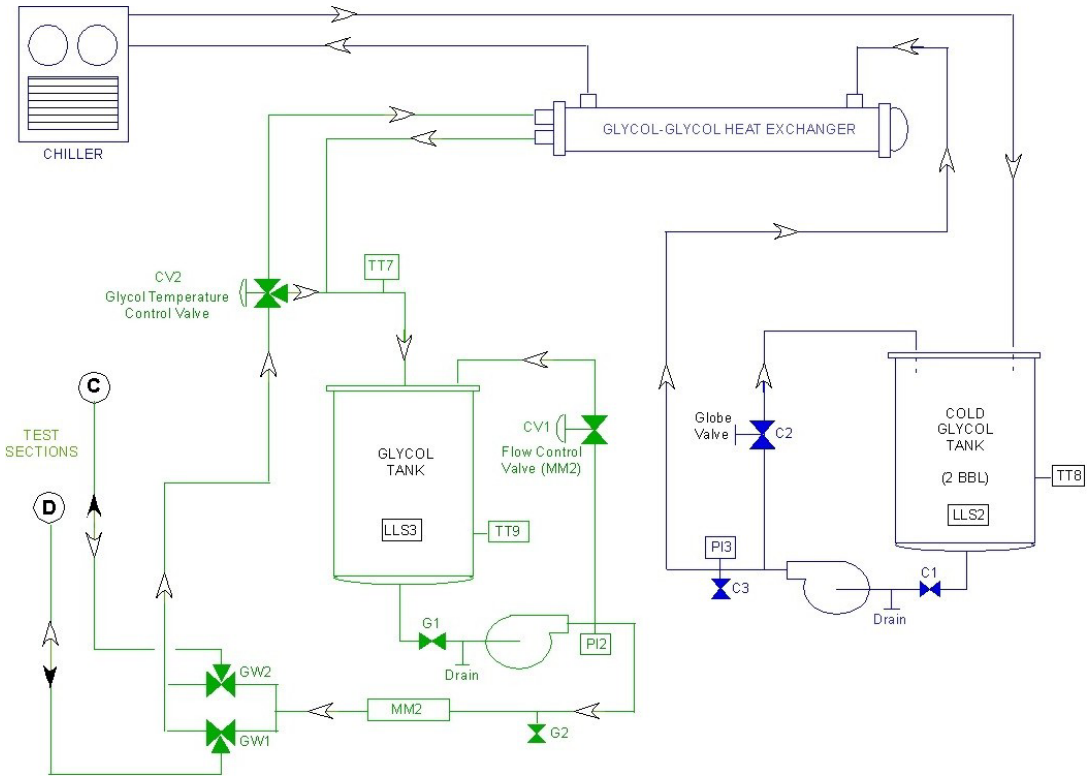


Figure 2.5 - Glycol Systems

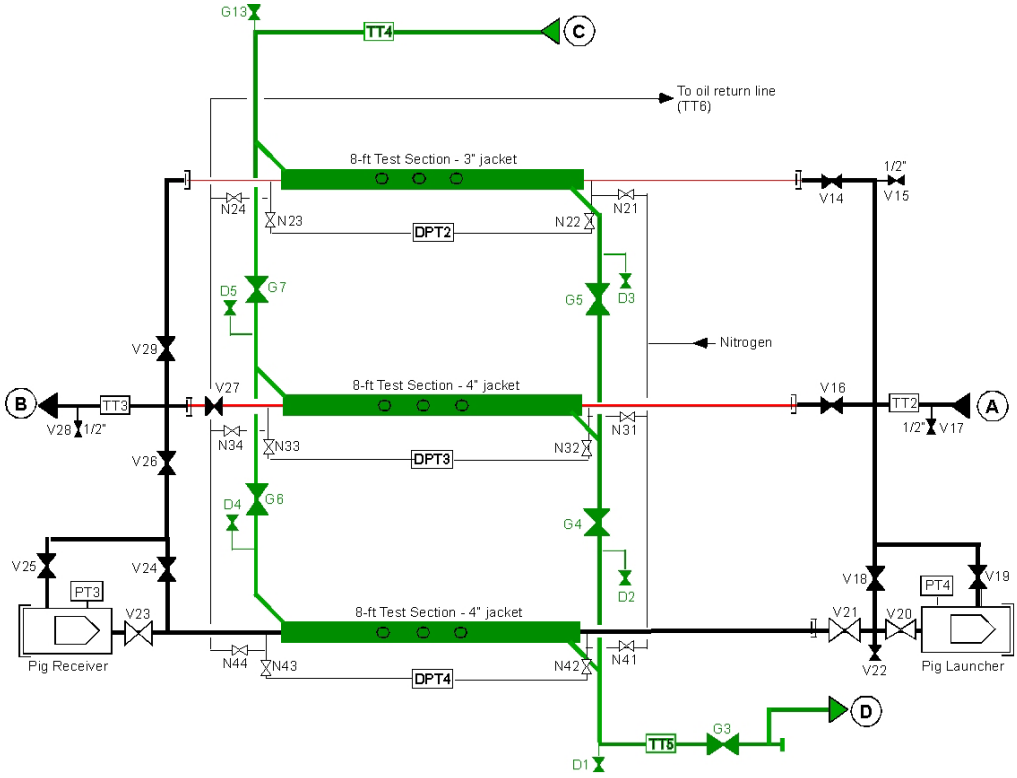


Figure 2.6 - Test Section

c. Single-Phase Studies

i. Facility Description

The single-phase flow loop was obtained from Alberta Research Council (Canada) and PetroCanada in 1995 and has since undergone major changes. The flow loop is a U-shaped, 164-ft long, 1.71 in. ID carbon steel pipe, jacketed with a 3.826 in. ID PVC annulus. Crude oil flows in the inner pipe and coolant – a 50% by weight glycol mixture – flows countercurrent in the annulus. Pumping, heating and cooling systems ensure control of flows and temperatures. Two impedance-heating sections ensure precise control of glycol and oil inlet temperatures in the test section. A heat-tracing system prevents paraffin deposition outside the test section.

The 164-ft long test section is divided into nine segments in which inlet and outlet temperatures for both oil and glycol, outside wall temperatures of the inside pipe, and oil pressure drops are recorded. Two non-jacketed, heat traced reference sections are located before and after the test section to gather data under non-depositing conditions. All measurements are recorded on an Intellution based data acquisition system. Two 3-ft long spool pieces can be removed at the end of each test for sampling and visualization.

A schematic of the single-phase flow loop is given in Fig. 2.7 and a test section schematic is given in Fig. 2.8.

The operating ranges are:

Oil temperature: 40-160 ºF
Oil flow rate: 0-2000 BPD
Oil pressure: 150 psig
Glycol Flow Rate: 0-2000 BPD
Glycol Temperature 40-160 ºF

The parameters recorded are:

Mass flow rate and density of glycol and oil.
Pressure drop and temperature of each segment in the test section.
Inlet and outlet temperatures.
Inlet and outlet glycol temperatures.
Oil pressure drop.
Other temperatures and pressures necessary for operating and safety.

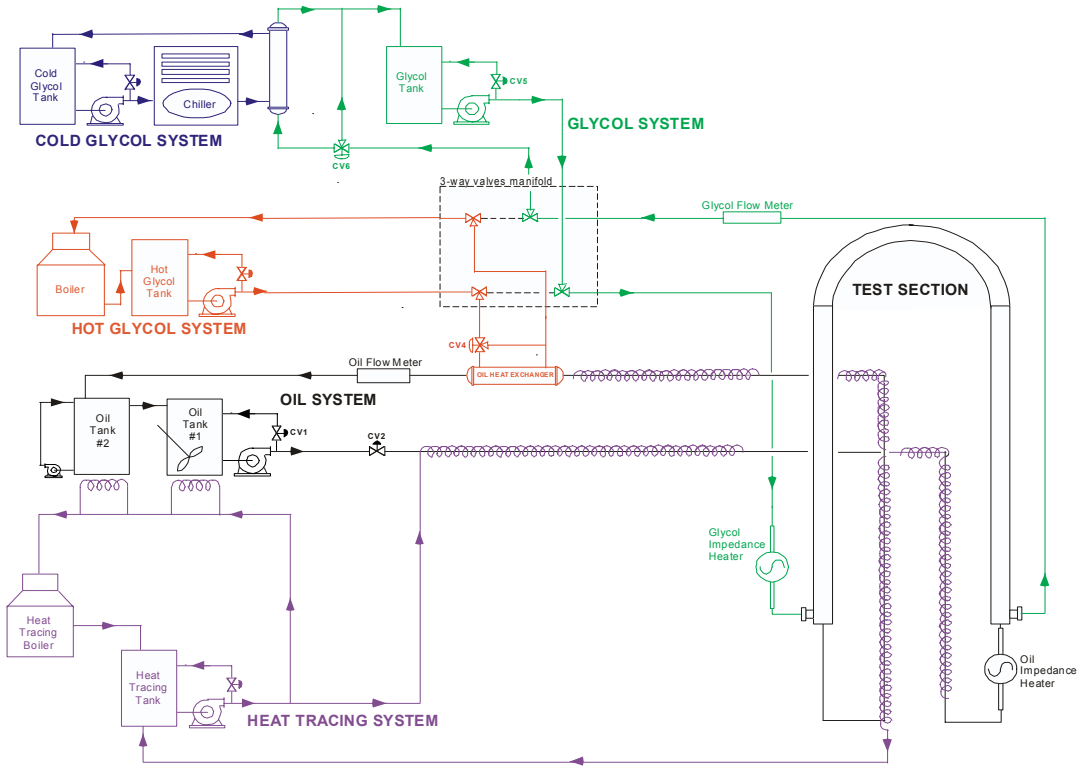


Figure 2.7 - Single-Phase Flow Loop Schematic

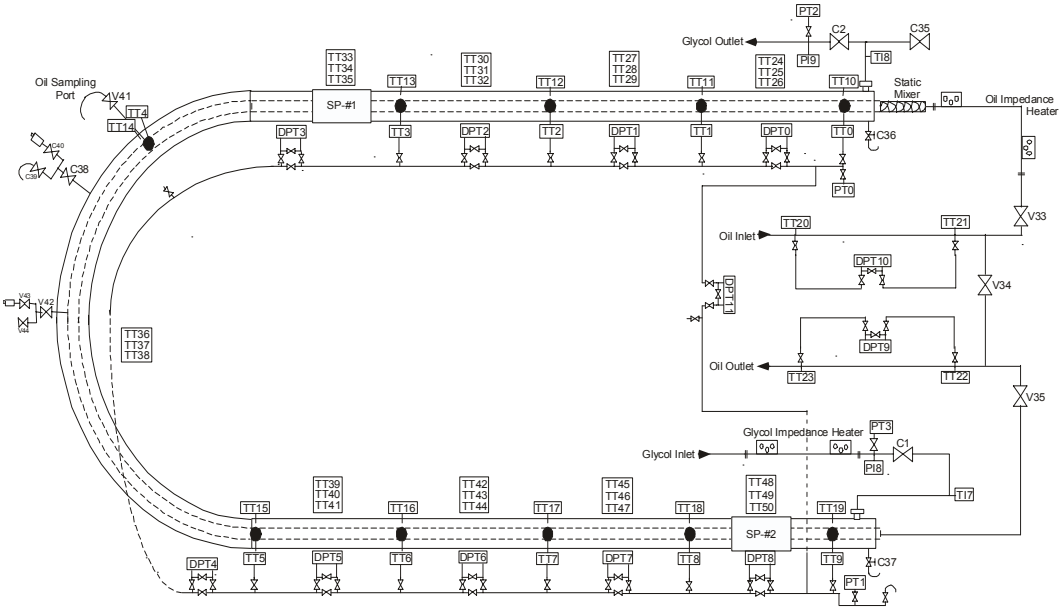


Figure 2.8 - Single-Phase Flow Loop Test Section Schematic

d. Two-Studies

i. Facility Description

The multiphase flow loop works on the same principle as the single-phase flow loop, except that natural gas can be flowed under pressures up to 750 psig and under different flow pattern conditions.

The test section is 75-ft long and is divided into three main portions: a 25-ft long thermal developing section that allows establishment of the thermal profile in the oil, a 25-ft long test section divided into five segments to monitor the paraffin deposition phenomenon, and a 5 ft-long retrievable spool piece that allows sampling and observation. The flow loop is inclinable from –2 degrees downward to vertical upward flow. Oil flows in the 2-in. inside pipe and glycol circulates countercurrent in a 4-in. CPVC annulus. A device allows for on-line measurement of the wax thickness following the Liquid Displacement – Level Detection (LD-LD) method extensively described in the previous reports.

Pumping, heating, cooling and heat tracing systems allow control of the facility. Process values are monitored and recorded using an Intellution FIX-based distributed control system (DCS). Schematics of the facility are given in Figs. 2.9 and 2.10.

The multiphase flow loop operating ranges are:

Oil flow measurable rate:	0 – 4,500 BPD
Gas Flow Rate:	0 – 2 MMscfd
Glycol flow rate:	0 – 3,500 BPD
Oil & Gas Temperature:	40°F – 160°F
Glycol Temperature:	40°F – 160°F
Oil & Gas Pressure:	200 – 750 psig
Pipe:	2-in. Sch.40 stainless steel pipe.

The recorded parameters on the flow loop are:

- Mass flow rates and densities of oil/gas/ glycol.
- Inlet/Outlet two-phase mixture and glycol temperatures in the test section.
- Temperature profile in the 25-ft test section (6 locations, oil/gas and glycol).
- Pressure drop in the thermal developing section and test section.
- Inside pipe outside wall temperatures (0, 45, 90, 135, 180 degrees).
- Gamma densitometer (flow pattern) and liquid holdup.

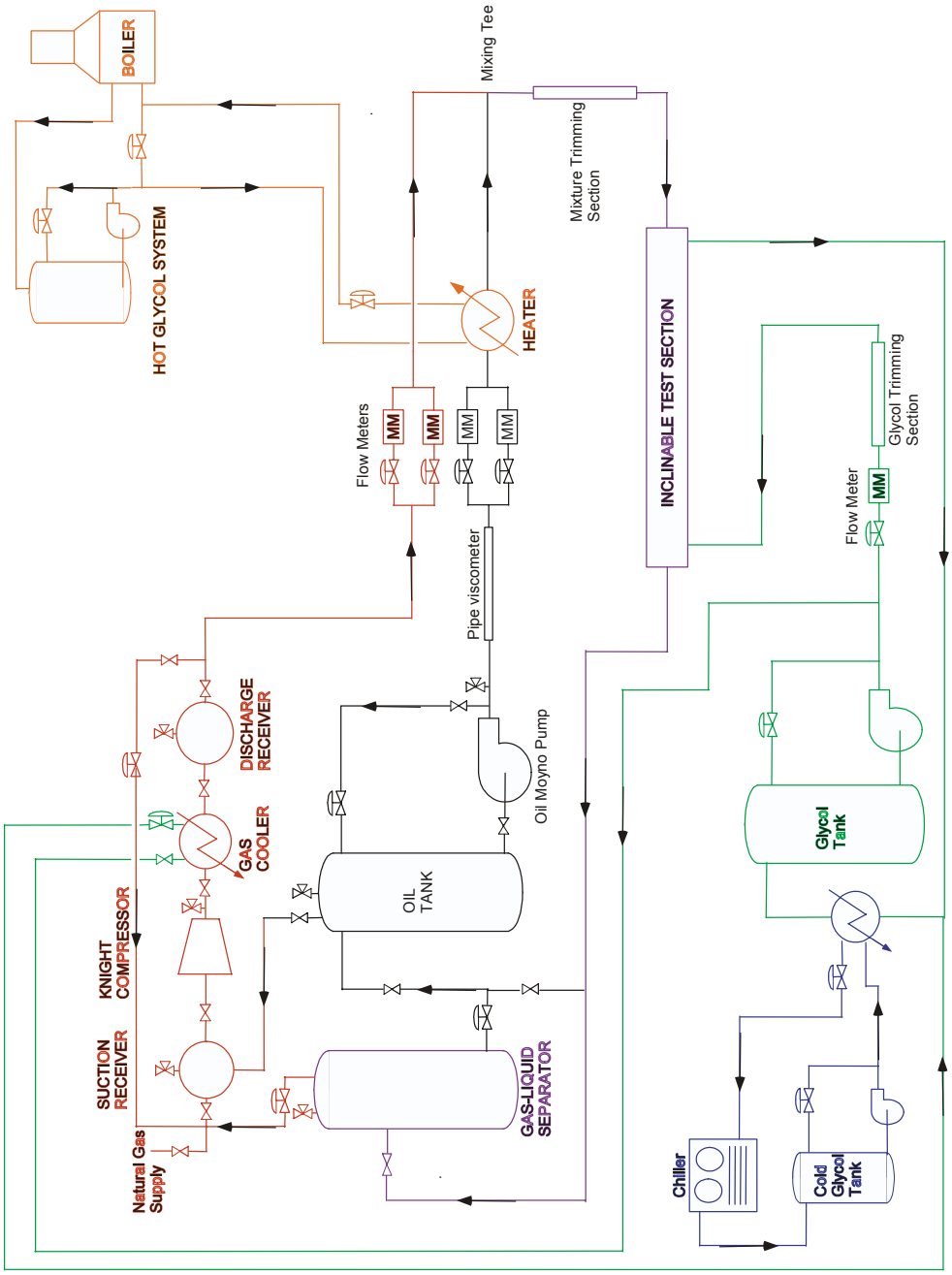


Figure 2.9 – Multiphase Flow Loop Process Flow Diagram

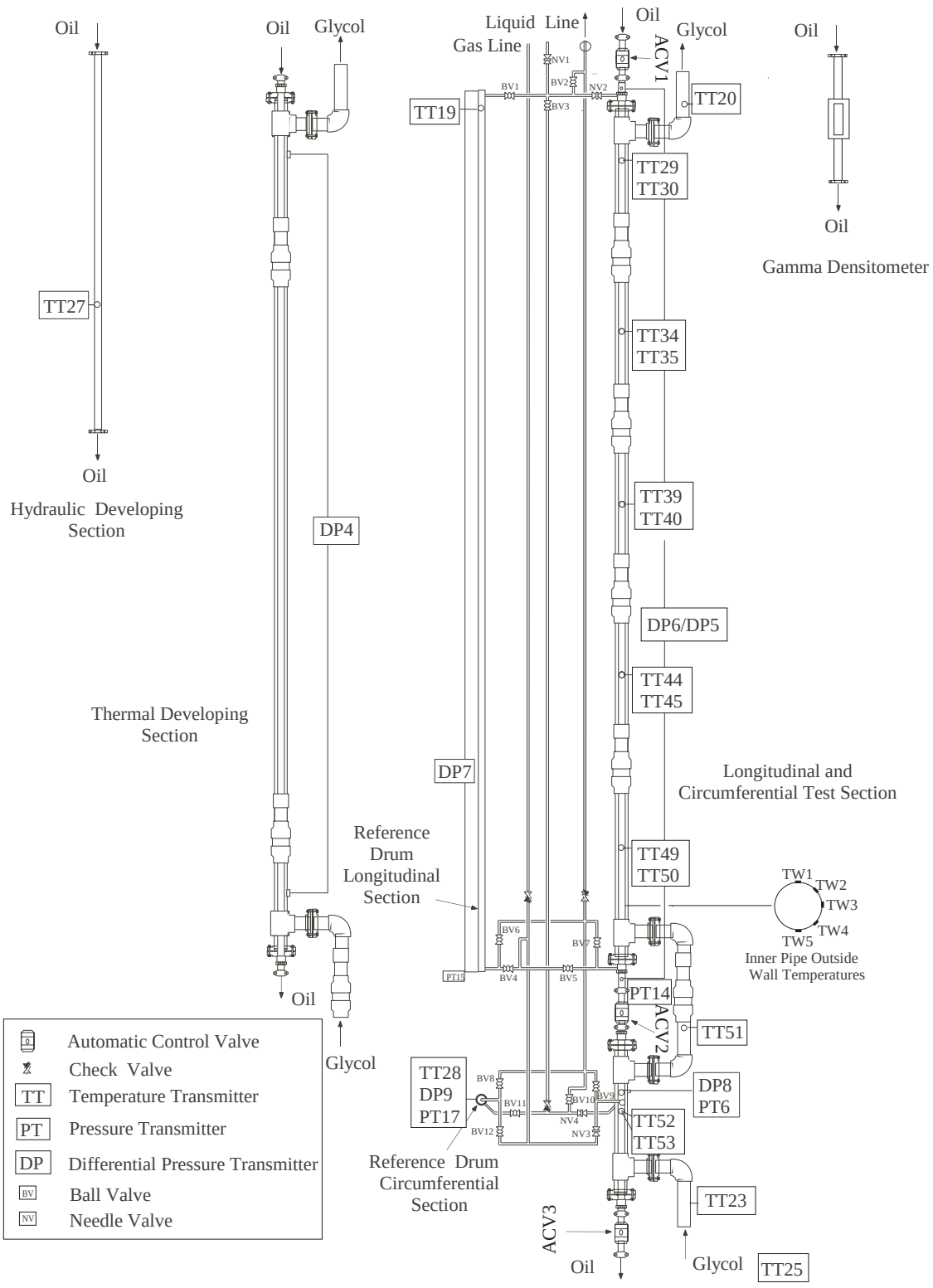


Figure 2.10 - Schematic of Test Section

e. Three-Phase Studies

i. Modification Status

The addition of the water system on the multiphase flow loop is still ongoing. All plumbing is now complete and the oil-water separator has been pressure tested. The instruments and instrumentation wires are in place. After completing the transformers upgrade in late August, the water pump is now being hooked-up. Efforts in the coming months will concentrate on connecting the new instruments and controls to the existing acquisition system and modifying the user-interface and control routines to accommodate oil-water-gas tests. This phase will be done after the last two oil-gas tests scheduled with Garden Banks. Commissioning is anticipated shortly thereafter.

Figure 2.11 – Construction of Water System

f. Cold Finger Apparatus

i. Description

The cold-finger apparatus can be used to correlate wax deposition to temperature differences between the bulk and wall. It consists of a hot bath to maintain the temperature of the bulk oil sample above or below its cloud point, a rotating stirrer to circulate oil and a cold finger probe. The cold finger probe consists of a steel cylinder in which cold glycol circulates. To ensure the glycol flow rates on each of the probes are identical during the tests, flow meters have been installed at the inlet of each cold finger cell as can be seen in Fig. 2.12. The speed of the oil stirrer can be adjusted. Paraffin deposits on the surface of the cold finger via molecular diffusion.

With the current setup, four tests with different fluids can be performed simultaneously under the same conditions.

Figure 2.12 - TUPDP Cold-Finger Device

3. Results and Discussions

a. Small-Scale Studies

i. Long-Term Deposition Test (WAX2003-010)

At the last ABM, the test results from the long-term (27 days) deposition test in the 1.5-in. diameter test section were reported. Afterwards, tests in the 1.0-in. and 0.5-in. diameter test sections were conducted with the same Reynolds number of 6300.

- ***Deposition Test in 1.0-in. Diameter Test Section (WAX2003-017)***

The test conditions were:

Oil Temperature: 105ºF
Oil Flow Rate: 570 BPD
Oil Velocity: 6 ft/sec
Oil Reynolds Number: 6300
Glycol Temperature: 75ºF
Glycol Flow Rate: 1600 BPD
Facility: 1.0-in. diameter Test Section
Flow Direction: Co-current Flow
Duration: 7 days
Shear Stress: 14 Pa

The oil and glycol temperatures were fairly stable, but the oil flow rate was not stable enough and resulted in non-continuous DP data. The thickness values calculated using the DP measurements were 0.8 mm toward the end of testing. The buildup of the wax deposit can be divided into three phases. For the first three days, a quick buildup was observed and deposit thickness reached about 0.8 mm. During the next two days, the thickness dropped to 0.6 mm and began to buildup again until it reached 0.8 mm. A possible reason for this decrease in thickness might be shear stress. During the last two days, the thickness stabilized at 0.8 mm. At shutdown, a large amount of hard deposit was found on the pipe wall. Samples were taken after 24 hrs and at the end of the test.

- ***Deposition Test in 0.5-in. Diameter Test Section (WAX2003-019)***

The test conditions were:

Oil Temperature: 105ºF
Oil Flow Rate: 333 BPD
Oil Velocity: 10.3 ft/sec
Oil Reynolds Number: 6300
Glycol Temperature: 75ºF
Glycol Flow Rate: 1600 BPD
Facility: 0.5-in Diameter Test Section
Flow Direction: Co-current Flow
Duration: 7 days
Shear Stress: 43 Pa

The oil flow rate, glycol flow rate and glycol temperature were fairly stable. Oil temperature control was achieved in a manual mode. Manual control resulted in oil temperature control of ± 2°F. Thickness values calculated using the DP measurements were 0.35 mm toward the end of testing. The buildup of the wax deposit can be divided into two phases. For the first day, a continuous buildup was observed and the deposit thickness reached about 0.25 mm. Over the next five days, a stair-step growth was observed and the thickness eventually stabilized at 0.4 mm. A possible reason for this decrease in thickness might be due to the extremely high shear stress of 43 Pa. At shutdown, a very hard deposit was found.

ii. Modification of the Facility

The above tests showed that the oil outlet temperature oscillates with ambient temperature; a possible reason is that the oil absorbs heat while it flows through the developing section and before it enters the test section. In an attempt to eliminate this oscillation, TT2 was moved to the front of the test section. The modification is shown in Fig. 3.1. First, TT2 was changed to a thermocouple from an RTD. The probes were then connected to the front of the test sections through the DP ports. TT2 now measures the oil temperature as the oil enters the jacketed section rather than before the developing section.

Deposition tests in the 0.5-in. and 1.0-in. diameter test sections were repeated after completing the modifications to see if the data were reproducible.

- ***Repeat Test in 1.0-in. Diameter Test Section (WAX2003-032)***

The test conditions were:

Oil Temperature: 105ºF
Oil Flow Rate: 570 BPD
Oil Velocity: 6fft/sec
Oil Reynolds Number: 6300
Glycol Temperature: 75ºF
Glycol Flow Rate: 1600 BPD
Facility: 1.0-in. Diameter Test Section
Flow Direction: Co-current Flow
Duration: 3.5 days
Shear Stress: 14 Pa

The oscillations of oil outlet temperature were eliminated. All the controls are now fairly stable, resulting in a smoother DP curve. The thickness values calculated using DP data was 0.8 toward the end of testing.

WAX2003-32 was a repeat test of WAX2003-17, the data do not match perfectly, but the performances are quite similar.

- ***Repeat Test in 0.5-in. Diameter Test Section (WAX2003-031)***

The test conditions were:

Oil Temperature: 105ºF
Oil Flow Rate: 333 BPD
Oil Velocity: 10.3 ft/sec
Oil Reynolds Number: 6300
Glycol Temperature: 75ºF
Glycol Flow Rate: 1600 BPD
Facility: 0.5-in. Diameter Test Section
Flow Direction: Co-current Flow
Duration: 4 days
Shear Stress: 43 Pa

All the controls were fairly stable. The oscillations in oil temperature were because the ambient temperature is high enough to heat the oil to the test temperature without the aide of the heater. The thickness values calculated based on DP measurements were 0.35 mm toward the end of testing. Comparable thicknesses were obtained for the repeat test.

- ***Depletion Test***

After the 27-day test was reported, there were some discussions as to whether the plateau of the thickness was because of wax depletion. A special test was designed to investigate this issue. The oil tank was first loaded with approximately 1 bbl of oil. The test was run until the thickness plateaued and then another bbl of fluid was loaded in the oil tank. If the deposit increased again, this would mean that depletion was taking place. If the deposit thickness remained the same, there would be no depletion.

The thickness values calculated using DP data were 1.2 mm during first days of testing. There was an increase in the glycol flow rate from about 1500 BPD to 1600 BPD. This was due to an unexpected restart.

There is a gradual increase in DP, indicating additional wax deposition after the addition of the fresh oil. Therefore, it is believed that the depletion of the oil is an issue to be addressed in future testing programs.

iii. Oil-Water Tests

Oil-water two-phase tests with water cuts of 25%, 40% and 75% were conducted in the 1.5-in. diameter test section with an oil flow rate of 850 BPD, which is the maximum stable flow rate of the oil pump.

- ***25% Water-Cut Test (WAX2003-43)***

The test conditions were:

Mixture Temperature: 105ºF
Mixture Flow Rate: 850 BPD
Mixture Velocity: 3.9ft/sec
Mixture Reynolds Number: about 6000
Glycol Temperature: 75ºF
Glycol Flow Rate: 1600 BPD
Facility: 1.5-in. Diameter Test Section
Flow Direction: Co-current Flow
Duration: 4 days

All the controls were fairly stable. A thick deposit with a rough surface was formed at the end of the test. To determine the apparent viscosity of the oil-water mixture for the thickness calculations, an oil-water mixture was flowed through the 1.5-in. diameter test section at 105ºF at different flow rates. DP data across the test section were taken and the apparent viscosity was calculated. It was found that the viscosity of this mixture is 1.05 times that of South Pelto crude oil. The growth of the deposit is quite similar to that of single-phase flow and can be clearly divided into two phases. For the

first 1.5 days, the deposit increased quickly and reached 1.2 mm. For the next 1.5 days, the deposit thickness stabilized at 1.2 mm. For the single-phase South Pelto test at the same test conditions, the deposit reached 0.8 mm after 2 days. To verify this result, a boroscope measurement was made to determine the thickness. A picture is shown as Fig. 3.2. The picture shows a thickness of 1.1 mm, which matches the thickness calculated using the DP data. Two pictures of the deposit surface were also taken and are shown as Fig. 3.3. It can be observed that the surface is very rough and there are structures developing on the surface.

Another key issue for the oil-water test is to make sure the oil and water are well mixed and that the emulsion is stable. A picture was taken of a mixture sample that was obtained from the flow line, as shown in Fig. 3.4. This picture shows a well mixed dispersion.

- ***40% Water-Cut Test (WAX2003-44)***

The test conditions were:

Mixture Temperature: 105ºF
Mixture Flow Rate: 850 BPD
Mixture Velocity: 3.9 ft/sec
Mixture Reynolds Number: about 6000
Glycol Temperature: 75ºF
Glycol Flow Rate: 1600 BPD
Facility: 1.5-in. Diameter Test Section
Flow Direction: Co-current Flow
Duration: 3 days

All the controls were fairly stable. A thick soft deposit with a rough surface was found at the end of the test.

The DP performance is very different from the previous test. Significant abrupt fluctuations were observed in DP measurements. No reasonable explanation for the fluctuations could be found at this time. In comparison with a dry South Pelto oil test at the same test conditions, a faster deposition is observed, i.e., dry oil deposition reached 1.7 mm thickness in 4 days while the oil with 40% water-cut reached 2 mm deposit thickness in 2 days.

- ***75% Water-Cut Test (WAX2003-43)***

The test conditions were:

Mixture Temperature: 105ºF
Mixture Flow Rate: 850 BPD
Mixture Velocity: 3.9 ft/sec
Mixture Reynolds Number: about 550
Glycol Temperature: 75ºF
Glycol Flow Rate: 1600 BPD
Facility: 1.5-in. Diameter Test Section
Flow Direction: Co-current Flow
Duration: 3 days

All the controls were fairly stable.

The apparent viscosity of this mixture was found to be 13.3 times that of single-phase South Pelto crude oil using the procedure described in the 25% water cut test. This reduces the Reynolds number to 550, making the flow laminar.

At shutdown, a thick soft deposit was found. The thickness values calculated using DP data was 0.75 mm. Growth of the deposit is continuous and more like the single-phase deposits. For single-phase South Pelto and the same test conditions, the deposit reached 0.8 mm after 2 days and the exact same results were obtained for the 75% water cut test. However, this test was for laminar flow, which is different from the single-phase test.

To verify the calculated thickness, a boroscope measurement was made. A picture is shown in Fig. 3.5. The picture is not very clear, but shows the thickness is about 2.0 mm, which does not match the thickness calculated using the DP data. This difference may have resulted in using a DP meter that was not suitable for laminar flow measurements.

iv. Conclusion

Tests in the three test sections with the same Reynolds number of 6300 have been completed. The oil and glycol inlet temperatures were 105ºF, and 75ºF, respectively for all tests. For the 1.5-in. diameter test section, deposit thickness reached 1.6 mm after 20 days. For the 1.0-in. diameter test section, deposit thickness reached 0.8 mm after 7 days. For the 0.5-in. diameter test section, deposit thickness reached 0.4 mm after 7 days. All of these above tests have been repeated and the results were reproducible. Unfortunately, depletion was confirmed and a bigger oil tank is needed.

Three oil-water two-phase tests were done to investigate the effect of water. All three tests showed faster wax buildup than the single-phase tests.

v. Future Work

After completion of the depletion test, four single-phase comparison tests will be made to investigate the effect of velocity and shear stress. The test matrix is shown in Table 3.1. Tests with the same velocity and shear stress values in different test sections will also be conducted. Two sets of these tests are in the transition region and two are at a very low Reynolds number of 4000.

Table 3.1 - Test Matrix

RE	Q(BPD)	v (ft/sec)	Shear(Pa)	TS
6300	330	10.0	43.0	0.5"
	570	6.0	14.0	1.0"
	850	3.9	6.3	1.5"

v (ft/sec)	Q(BPD)	RE	Shear(Pa)	TS
3.9	127	2575	8.9	0.5"
	360	4330	7.3	1.0"
	850	6300	6.3	1.5"
Shear(Pa)	**Q(BPD)**	**RE**	**v (ft/sec)**	**TS**
6.3	108	2200	3.3	0.5"
	333	4003	3.6	1.0"
	850	6300	3.9	1.5"

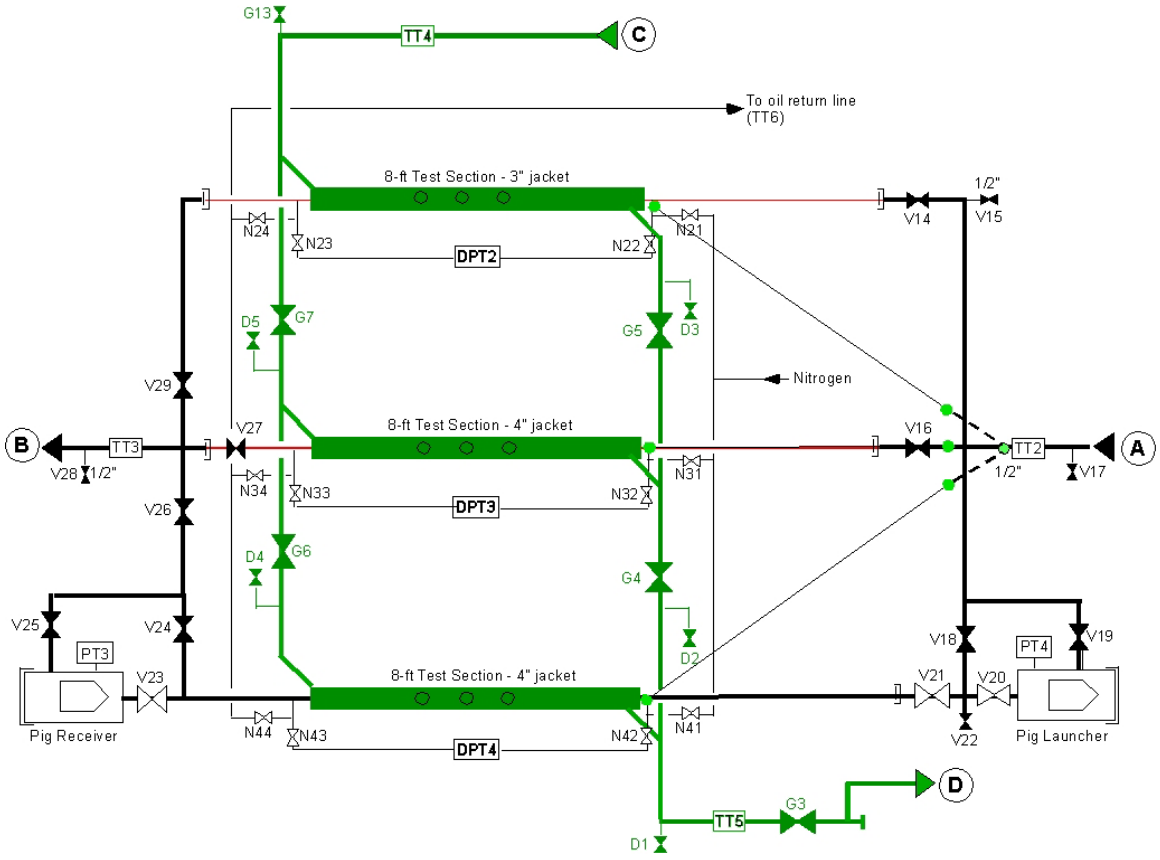


Figure 3.1 - Test Section after Modification

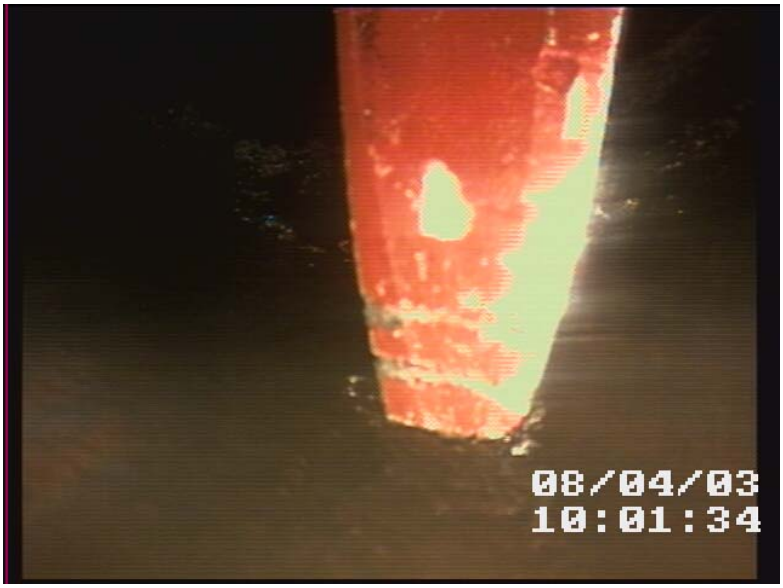


Figure 3.2 - Boroscope Measurement

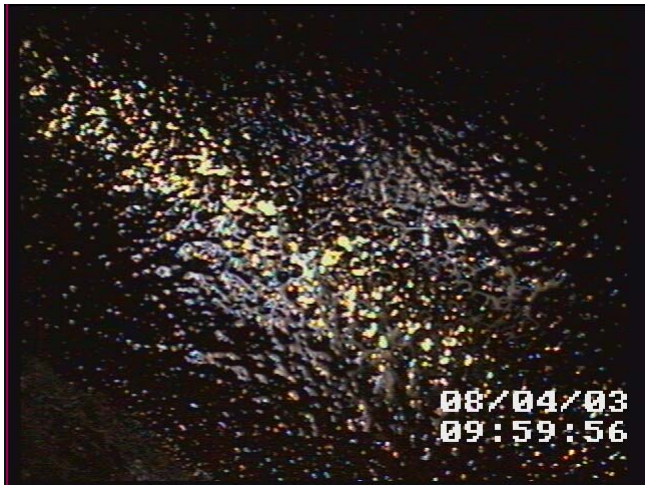


Figure 3.3 - Deposit Surface

Figure 3.4 - Mixture Sample

Figure 3.5 - Boroscope Measurement

b. Single-Phase Studies

i. Data Processing

Once the shutdown is completed, measurements and data processing is necessary for thickness estimation and phenomenological study. After the spool pieces are taken out, the procedure for data processing can be described as follow:

- ***Visualization and Sampling:***

Using a boroscope, the surface of the deposit is explored inside the spool pieces. Uniformity and porosity can be qualitatively characterized. Samples of the deposit are also taken for further analysis with the DSC apparatus for oil fraction determination.

Pictures are taken for boroscope thickness determination. With this technique, a picture of a probe inserted into the deposit is taken and processed. Marks in the probe work as references for thickness determination by comparing the distance between the reference marks with the distance between the surface of the deposit and any of the marks.

- ***Liquid Displacement-Level Detection (LD-LD):***

With this process, a clean pipe, with the same geometrical characteristics of the spool piece is filled up with water, the water is displaced into the spool piece afterwards; the difference between the water levels is a measurement of the thickness of the deposit inside the spool piece. The measurement is done three times to verify repeatability.

The spool pieces are also washed with Methyl Ethyl Ketone (MEK) after each test to remove the oil on the deposited, otherwise it would be counted as solid wax for the LD-LD method.

- ***Pressure Drop Thickness Determination:***

After the data is downloaded, the thickness of the deposit is calculated at every data acquisition time step based on the fact that during wax build up the hydraulic radius decreases, increasing this way the pressure drop of the oil flow. For the laminar case (CBI tests), the thickness calculation can be reduced to the following expression:

$$\delta = \frac{d}{2}\left(1 - \frac{\left.\frac{dP}{dl}\right|_{ref} \mu_t \dot{m}_t \rho_t}{\left.\frac{dP}{dl}\right|_{t} \mu_{ref} \dot{m}_{ref} \rho_{ref}}\right)^{1/4} \quad \text{Eq. 1}$$

For the turbulent case, the expression will be:

$$\delta = \frac{d}{2}\left(1 - \frac{\left.\frac{dP}{dl}\right|_{ref} f_t \dot{m}_t^2 \rho_{ref}}{\left.\frac{dP}{dl}\right|_{t} f_{ref} \dot{m}_{ref}^2 \rho_t}\right)^{1/5} \quad \text{Eq. 2}$$

- ***Heat Transfer Based Thickness Determination:***

Another method to calculate the thickness of the deposit relies on the fact that the wax layer creates an additional resistance for the heat to flow, this way, the outlet temperature of the oil will increase as the thickness of the deposit increases. The general case, for thickness calculation based on heat transfer yields:

$$\delta = \frac{d}{2} \cdot \frac{d}{2e^{\frac{2Kw}{d_{out}}\left[\left(U_{ref} - U_t\right)\frac{d_{out}}{d}\left(\frac{1}{hoil_{ref}} - \frac{1}{hoil_t}\right) - \left(\frac{1}{hgl_{ref}} - \frac{1}{hgl_t}\right)\right]}} \quad \text{Eq. 3}$$

Different methods, based on the same principle were used before; however, none of those were capable of including the cooling phase data set. For the above expressions, a reference point, with no deposition (beginning of the test), is compared with a point at time "t". The differences in outlet oil temperature and pressure drop are then interpreted as deposition.

ii. Testing

Since the last Advisory Board Meeting, some changes in the start up procedure have been made. Once the fluids are heated to the desired melting point, the test section is by passed so the cooling down period takes place only inside the heat exchanger (oil system). This

ensures there is no deposition inside the test section and that the data at time zero will correspond with zero thickness. Observations about the early deposition time can be easily made with the new procedure.

All the tests corresponding to the modified test matrix were completed and are summarized in the Table 3.2.

Long term tests were added to the initial test matrix due to questions about the characteristics of the phenomena for longer periods for higher viscosity fluids. Previously, the results from South Pelto crude oil and Garden Banks condensate tests were similar in growth rate; observing a higher slope at the beginning of the test and no decrease in it afterwards. However, CBI behavior differs as such that a constant and/or very small slope of the thickness of the deposit versus time is observed.

- ***ΔT Effect***

Three tests were run to study the effect of ΔT (refer to Table 3.2, tests 1, 2, 3). As a quick approximation, the effect of the ΔT may be seen in Table 3.3, based on Fick's Law of Diffusion and the following assumptions: wall temperature equal to glycol temperature, diffusion coefficient as a constant over the viscosity (Hernandez 2002), and temperature gradient (dT/dr) proportional to ΔT (same flow rate for all tests).

Based on the previous results, the tests with 15º ΔT and 45ºF ΔT have 0.68 and 0.61 times the potential of the 30ºF ΔT for depositing. Tables 3.4a – 3.4b show the numerical results of the LD-LD analyses.

The previous results shown (before MEK wash) are in agreement with the assumptions described below; however, the tendencies of the curves are in disagreement with the previous fluids, where higher deposit thickness were calculated for higher temperatures differences. A possible cause for this is the viscosity effect. The CBI viscosity shows a significant change with temperature; thereby affecting the diffusivity factor. Measurements after the MEK wash shows, on the other hand, a tendency to form deposits with higher oil content as the ΔT increases.

From deposit thickness versus time calculations, the comparisons were made by using pressure drop and heat transfer methods. One can conclude that the heat transfer method applies better for CBI thickness calculations since the temperature changes are better defined in laminar tests. A fairly constant slope of thickness growth can be noted; a phenomenon not observed for either South Pelto or Garden Banks tests. For these tests, higher slopes were observed at the beginning of the tests and a significant decrease after a period of time.

Another observation from the thickness versus time is the constant slope for the different tests. The different thicknesses are determined with the start-up effect when the flow changes from an isothermal condition to non-isothermal flow takes place. The actual data processing tool that integrates the cooling period reveals the effect of the temperature gradient.

Different wax characteristics were observed based on visual inspection, where a tendency for softer deposits was observed for higher ΔT's. This tendency can be interpreted as higher oil content in the deposit.

- ***Oil Inlet Temperature Effect***

The oil inlet temperature effect on the deposition was studied with three tests (Table 3.2 - tests 4, 5, 6). The flow rate and ΔT were constant while the oil inlet temperature changed. The deposition potential was compared with a base case. The results are summarized in Table 3.5.

Thicker deposits are expected at 95ºF oil inlet temperature than the reference case (85ºF oil inlet temperature) due to the lower oil viscosity near the wall, affecting the diffusivity factor. A contrary behavior was observed as shown with LD-LD measurements in Table 3.6 (A & B).

Comparing measurements before and after the MEK wash, higher oil contents were observed at lower temperatures. For the 75°F oil inlet temperature test, nearly 50% was removed

with MEK wash, compared with 20% removed for the 85ºF oil inlet temperature case; for the third case, the measurement remains within the error band of the original one (before the MEK wash).

The different deposit thicknesses observed from different oil inlet temperatures clearly show a dependence on the oil inlet temperature. This phenomenon was not clearly observed during the South Pelto tests (Lund 1998) where no significant differences in thickness were measured between tests at 125, 105 and 85ºF.

♦ ***Flow Rate Effect***

The flow rate effect on paraffin deposition was studied with tests 7 - 12. ΔT and oil inlet temperature were fixed while the flow rate varied within the laminar region (due to pump limitations). Theoretically, according to the Fick's Law, the main difference between the tests comes from the temperature gradient within the pipe; assuming the same viscosity for all the tests. LD-LD results from the different tests are shown in Tables 3.7A and 3.7B.

From the obtained results, the effect of the flow rate on the fluid was not evident (based on LD-LD measurements). Previous results with South Pelto in laminar flow showed a similar trend.

♦ ***Deposition Time Effect***

The deposition rate effect was studied by completing five tests with the same conditions but different deposition times varying from 3 hours to 96 hours. Good repeatability was encountered for the different tests. The LD-LD results are reported in Tables 3.8 A & B. A change in the slope seems to occur between 24 and 96 hours. Different phenomena may contribute to the deposit growth decrease: Insulation effect (smaller temperature gradient and higher interface temperature) due to a thicker deposit and/or increment of wax fraction inside the deposit. Shear effect as a mechanical removal mechanism increased due to a hydraulic diameter reduction; or depletion problems due to the amount of wax crystals available for deposit at the test condition.

iii. Conclusions

♦ ***Experimental Program***

Based on the tests conducted with CBI, the following were observed:

- Better temperature control and easier interpretation of the data were accomplished for the tests by cooling outside the test section. With the new procedure, the effect of the temperature gradient was more evident at the beginning of the test.

- The new data processing tool for thickness calculation based on pressure drop and outlet temperature changes provide better results when changes in the oil properties were considerable. With this new code, an interpretation of the cool-down period can be included for those tests where the cooling took place inside the test section.

- The tendency of building thicker deposits as the temperature gradient increases could not be observed for CBI. The viscosity of the fluid is thought to play an important role since there are considerable changes that affect the diffusivity phenomena. The effect was not significant in fluids South Pelto oil and Garden Banks condensate.

- Higher wax fractions inside the deposit were encountered at higher temperatures as well as harder deposits (not measured). The results were confirmed by higher differences between the LD-LD measurements before and after the MEK wash. One of the reasons is believed to be the lower viscosity that increases the mass diffusion.

- The effect of the flow rate in the laminar regime was not as evident as in the turbulent flow. The same behavior was observed for tests with South Pelto oil. Similar to South Pelto oil and Garden Banks condensate, higher deposits were measured in spool piece 1 than in spool piece 2 for laminar flows.

- Different thickness growth behavior was observed for CBI. For South Pelto oil and Garden Banks condensate, higher slopes were observed at initial times followed by a curve with nearly zero slope; possibly due to depletion problems, insulation, or shear effect. For CBI, a nearly constant and very low slope was observed for all tests. Differences between the thicknesses depended on very early time behavior due the temperature gradient effect on the oil.

- Gel formation was observed in the spool pieces after shutdowns. A possible relationship between the amount of gel and the wall temperature was evidenced with less gel formation as the wall temperature increased. Enrichment of the "gel layer" due to the mass diffusion is speculated as one of the mechanisms for wax deposition for CBI. The presence of the gel was not observed with previous fluids possibly due to the lower viscosity values.

iv. Future Work

- Transfer the fluid back into the tank and load the facility with Caratinga oil (Petrobras).

- Start the fluid validation for the fourth fluid, including viscosity analysis, HTGC analysis. Design the test matrix based on the properties of the fluid and facility limitations.

- Improve the current single-phase paraffin deposition model by including the thermal diffusion term.

Table 3.2 - CBI Test Matrix

Test #	Objective	Variable	Conditions
1	Effect of ΔT	45 ºF ΔT	Qo=1500 BPD; t=24 hours; Toil=85ºF
2	Effect of ΔT	30 ºF ΔT	Qo=1500 BPD; t=24 hours; Toil=85ºF
3	Effect of ΔT	15 ºF ΔT	Qo=1500 BPD; t=24 hours; Toil=85ºF
4	Effect of Oil Inlet Temperature	Toil=95 ºF	Qo=1500 BPD; t=24 hours; ΔToil=30ºF
5	Effect of Oil Inlet Temperature	Toil=85 ºF	Qo=1500 BPD; t=24 hours; ΔToil=30ºF
6	Effect of Oil Inlet Temperature	Toil=75 ºF	Qo=1500 BPD; t=24 hours; ΔToil=30ºF
7	Effect of the Flow Rate	Qoil=200 BPD	t=24 hours; Toil=85ºF; ΔToil=30ºF
8	Effect of the Flow Rate	Qoil=600 BPD	t=24 hours; Toil=85ºF; ΔToil=30ºF
9	Effect of the Flow Rate	Qoil=900 BPD	t=24 hours; Toil=85ºF; ΔToil=30ºF
10	Effect of the Flow Rate	Qoil=1200 BPD	t=24 hours; Toil=85ºF; ΔToil=30ºF
11	Effect of the Flow Rate	Qoil=1500 BPD	t=24 hours; Toil=85ºF; ΔToil=30ºF
12	Effect of the Flow Rate	Qoil=1650 BPD	t=24 hours; Toil=85ºF; ΔToil=30ºF
13	Deposition Time Effect	t=3 hours	Qoil=1500 BPD, Toil=85ºF; ΔToil=30ºF
14	Deposition Time Effect	t=12 hours	Qoil=1500 BPD, Toil=85ºF; ΔToil=30ºF
15	Deposition Time Effect	t=24 hours	Qoil=1500 BPD, Toil=85ºF; ΔToil=30ºF
16	Deposition Time Effect	t=96 hours	Qoil=1500 BPD, Toil=85ºF; ΔToil=30ºF

Note: for all the runs, the glycol flow rate was set at 2000 BPD

Table 3.3 – Effect of ΔT. Impact on the Deposition based on Fick's Law of Diffusion

Test	1 (45ºF ΔT)	2 (30ºF ΔT)	3 (15ºF ΔT)
Wall Temperature	40ºF	55ºF	70ºF
Concentration gradient: $\frac{\partial C}{\partial T}\Big/\frac{\partial C}{\partial T}\Big\|_{30\Delta T}$	1.22	1.00	0.60
Diffusivity Factor: $D_{AB}/D_{AB}\|_{30\Delta T}$	0.37	1.00	2.03
Temperature Gradient Ratio $\frac{\partial T}{\partial r}\Big/\frac{\partial T}{\partial r}\Big\|_{30\Delta T}$	1.50	1.00	0.50
Product $\frac{\frac{\partial C}{\partial T} D_{AB} \frac{\partial T}{\partial r}}{\frac{\partial C}{\partial T}\Big\|_{30\Delta T} D_{AB}\|_{30\Delta T} \frac{\partial T}{\partial r}\Big\|_{30\Delta T}}$	0.68	1.00	0.61
Commentary: Based on these results, higher thickness can be expected for the 30ºF ΔT case and lower thickness by a factor of 0.68 and 0.61 for 45 and 15ºF ΔT respectively			

Table 3.4A – LD-LD Measurements before MEK. ΔT Effect

Test	1 (45ºF ΔT)	2 (30ºF ΔT)	3 (15ºF ΔT)
Spool Piece 1[mm]	0.37 (0.59)	0.62 / 0.70	0.50 (0.80)
Spool Piece 2 [mm]	0.26 (0.89)	0.29 / 0.43	0.19 (0.65)
Overall [mm]	0.31 (0.68)	0.45 / 0.56	0.35 (0.77)

Table 3.4B – LD-LD Measurements after MEK. ΔT Effect

Test	1 (45ºF ΔT)	2 (30ºF ΔT)	3 (15ºF ΔT)
Spool Piece 1 [mm]	---	0.58 / 0.46	0.50
Spool Piece 2 [mm]	0.06	0.12 / 0.11	0.18
Overall [mm]	0.33	0.35 / 0.28	0.34

Table 3.5 - Effect Oil Inlet Temperature. Impact on the deposition based on Fick's Law of Diffusion

Test	4 (Toil = 75ºF)	5 (Toil = 85ºF)	6 (Toil = 95ºF)
Wall Temperature	45ºF	55ºF	65ºF
Concentration gradient: $\frac{\partial C}{\partial T}\Big/\frac{\partial C}{\partial T}\Big\|_{30\Delta T}$	1.16	1.00	0.74
Diffusivity Factor: $D_{AB}/D_{AB}\big\|_{30\Delta T}$	0.53	1.00	1.64
Temperature Gradient Ratio $\frac{\partial T}{\partial r}\Big/\frac{\partial T}{\partial r}\Big\|_{30\Delta T}$	1.00	1.00	1.00
Product $\frac{\frac{\partial C}{\partial T} D_{AB} \frac{\partial T}{\partial r}}{\frac{\partial C}{\partial T}\Big\|_{30\Delta T} D_{AB}\big\|_{30\Delta T} \frac{\partial T}{\partial r}\Big\|_{30\Delta T}}$	0.61	1.00	1.21
Commentary: Based on these results, higher thickness can be expected for the 95ºF oil inlet temp. test and thicknesses of 0.61 and 1.21 times the thickness of the base case (85ºF oil inlet temp.)			

Table 3.6A – LD-LD Measurements before MEK. Oil Inlet Temperature Effect

Test	4 (75ºF Toil)	5 (85ºF Toil)	6 (95ºF Toil)
Spool Piece 1 [mm]	0.49 (0.70)	0.70 / 0.62	0.35 (0.50)
Spool Piece 2 [mm]	0.06 (0.20)	0.43 / 0.29	0.05 (0.17)
Overall [mm]	0.28 (0.62)	0.56 / 0.45	0.20 (0.44)

Table 3.6B – LD-LD Measurements after MEK. Oil Inlet Temperature Effect

Test	4 (75ºF Toil)	5 (85ºF Toil)	6 (95ºF Toil)
Spool Piece 1 [mm]	0.24	0.58 / 0.46	0.30
Spool Piece 2 [mm]	0.00	0.12 / 0.11	0.04
Overall [mm]	0.12	0.35 / 0.28	0.17

Table 3.7A – LD-LD Measurements. Flow Rate Effect

Test	7 (200 BPD)	8 (600 BPD)	9 (900 BPD)	10 (1200 BPD)	11 (1500 BPD)	12 (1650 BPD)
Spool Piece 1 [mm]	0.71	0.53	0.52	0.71	0.70 / 0.62	0.43
Spool Piece 2 [mm]	0.37	0.23	0.23	0.30	0.43 / 0.29	0.16
Overall [mm]	0.54	0.38	0.38	0.50	0.56 / 0.45	0.30

Table 3.7B – LD-LD Measurements. Flow Rate Effect

Test	7 (200 BPD)	8 (600 BPD)	9 (900 BPD)	10 (1200 BPD)	11 (1500 BPD)	12 (1650 BPD)
Spool Piece 1 [mm]	0.52	0.46	0.26	0.44	0.58 / 0.46	0.31
Spool Piece 2 [mm]	0.23	0.25	0.00	0.17	0.12 / 0.11	0.08
Overall [mm]	0.37	0.35	0.13	0.31	0.35 / 0.28	0.20

Table 3.8A – LD-LD Results before MEK. Deposition Time Effect

Test	13 (3 Hours)	14 (12 Hours)	16 (24 Hours)	15 (96 Hours)
Spool Piece 1 [mm]	0.46	0.36	0.62 / 0.70	0.94
Spool Piece 2 [mm]	0.13	0.32	0.29 / 0.43	0.75
Overall [mm]	0.30	0.34	0.45 / 0.58	0.84

Table 3.8B – LD-LD Results After MEK. Deposition Time Effect

Test	13 (3 Hours)	14 (12 Hours)	16 (24 Hours)	15 (96 Hours)
Spool Piece 1 [mm]	0.00	0.33	0.46 / 0.58	0.70
Spool Piece 2 [mm]	0.00	0.00	0.11 / 0.12	0.71
Overall [mm]	0.00	0.17	0.28 / 0.35	0.71

c. Two-Phase Studies

i. Two-Phase Flow Tests

A total of 21 multiphase tests (9 horizontal (0°) and 12 vertical (90°)) were conducted on the multiphase flow loop with the Garden Banks condensate. These 21 tests are composed of 13 original tests and 8 repeat tests. These repeat tests were performed to improve data quality (more stable glycol temperature and gas flow rate), as well as to avoid wax deposition during the startup phase. The test conditions involved flowing 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 all tests and the inlet glycol-water mixture temperature was 40°F (ΔT of 45°F) for 12 tests but only 43°F (ΔT of 42°F) for the other repeat tests. For the repeat tests the ΔT had to be slightly reduced to eliminate some temperature fluctuations. The system was under pressure of 350 psig during all these tests.

To reduce the fluctuations in the glycol temperature data, the inlet temperature of glycol was increased from 40°F from 43°F (i.e. the ΔT was slightly decreased from 45°F to 42°F); this change was necessary to allow the impedance heating section to compensate the glycol temperature fluctuations caused by the chiller. This adjustment significantly improved the temperature data, and therefore, it was decided to repeat most of the previous runs to improve the quality of data. Also, the startup procedure was changed to avoid deposition in the test section during the startup phase.

The two-phase tests covered a wide range of operating conditions and flow patterns often encountered in multiphase pipelines and wellbores, including stratified-smooth, stratified-wavy, slug and annular flow for horizontal pipes, and intermittent and annular flow for vertical pipes with oil superficial velocities ranging from 0.2 ft/s to 4 ft/s, and gas superficial velocities ranging from 0.5 ft/s to 30 ft/s. The glycol-water mixture flow rate was maintained at 2,000 BPD in all tests. Table 3.9 summarizes the completed tests. The "old startup procedure" refers to cooling while flowing oil and gas in the test section, whereas the "new startup procedure" bypassed the test section and uses cold gas to cool down the oil phase.

The original test matrices for the wax deposition tests are given in Tables 3.10 and 3.11.

ii. Test Description

- ***Melting Procedure***

1. Start the hot glycol system and circulate Garden Banks condensate through the test section (glycol jacket is empty).
2. Condensate is heated to a temperature approximately 30ºF above the wax appearance temperature (WAT).
3. Condensate is then circulated at about 1,500 BPD for approximately 8 hours to melt deposit.

- ***Old Startup Procedure***

1. Flow gas and condensate mixture through meter runs, into separator, bypassing the test section until separator temperature reaches 30 ºF above cloud point. Liquid from separator is transferred to oil tank and gas from separator returns to compressor.
2. Circulate two phase mixture through test section at high flow rates and chilled glycol countercurrent through jacket until test temperature is reached (i.e. 85 ºF). Note that some deposition occurs in test section with this procedure.
3. Adjust gas and condensate flow rates to desired test conditions.

- ***New Startup Procedure***

1. Same as step 1 in old startup procedure.
2. Open bypass to test section, stop oil flow and flow only gas through test section to remove condensate from test section. Isolate test section (inner pipe and jackets are empty).
3. Circulate cold glycol through gas cooler and flow cold gas through separator to cool down condensate in separator. Simultaneously, circulate condensate from separator to oil tank, through pump, meter

run and separator. Note that the test section is isolated during this step so no deposition occurs.

4. When condensate and glycol reaches test temperature, their flow rates are adjusted to test conditions. Test section is open to start the test.

♦ ***Steady State***

Once the test conditions and steady state are achieved, the inlet conditions are maintained for 24 hrs. Oil samples are taken every 8 hours for future analysis.

♦ ***Shutdown***

After the test is complete online LD-LD measurements are performed. Then, the test is shut-down and the test section is drained with natural gas. Glycol in the annulus is displaced using air. The spool piece is removed, samples taken and thickness measurements performed using offline LD-LD.

iii. Deposit Thickness Determination

The deposit thickness on the test section is determined by two methods. These methods are:

♦ ***Online LD – LD Method***

One of the most reliable methods used on the multiphase flow loop is the online Liquid Displacement – Level Detection (LD – LD) method, based on the comparison of volumes in the test section and a (clean) reference drum, when both are raised to vertical position. The deposit thickness in the test section is assumed to be uniform axially and radially. This method has been used in the past and was found to be repeatable within +/-0.2 mm.

♦ ***Spool Piece (Offline) LD – LD:***

A portable LD – LD device allows reliable thickness measurements after shutdown. The principle of the measurement is the same as the online LD – LD, but applied to the spool piece. The accuracy of the offline LD-LD is +/- 0.05 mm.

♦ ***Pressure Drop and Heat Transfer Methods:***

Pressure drop and heat transfer methods are successfully employed to measure the average thickness of the wax layer deposited on the pipe inside wall in our single-phase (oil) wax deposition tests. These measurements are useful to demonstrate the growth process of the wax layer along with the time. These techniques were thought to be too complicated to be used for measurement of wax thickness under multiphase conditions due to the indistinct relationships between the pressure gradient increase and the reduction of the pipe diameter and between the heat transfer change and the existence of the wax layer. However, after reviewing these methods again, we have found that they can be used under multiphase flow conditions based on a few reasonable assumptions.

♦ ***Pressure Drop Method***

This method is based on the concept that wax deposition in a pipe section reduces the hydraulic diameter of the flowing fluid inside the pipe, resulting in an increase in frictional pressure drop over the pipe section. For two-phase stratified flow, the frictional pressure gradient is

$$\frac{\partial p}{\partial l} = -\frac{\tau_C S_C + \tau_F S_F}{A} \tag{1}$$

where τ_C and τ_F are the shear stresses on the pipe inside wall by the gas core and liquid film, respectively,

$$\tau_F = f_F \frac{\rho_L v_F^2}{2} \tag{2}$$

$$\tau_C = f_C \frac{\rho_G v_C^2}{2} \tag{3}$$

The friction factors, f_F and f_C, at the wall in contact with the liquid film or the gas pocket are estimated from

$$f = C\,\mathrm{Re}^{-n} \tag{4}$$

where C = 16, n = 1 for laminar flow, and C = 0.046, n = 0.2 for turbulent flow in smooth pipe.

The Reynolds numbers for gas core and liquid film are defined using the hydraulic diameters.

Since the wax thickness is minimal compared with the pipe diameter, we can assume that the changes in the two-phase flow structure and fluid properties are negligible during the wax deposition. The relationships between the parameters in the above equations can be expressed as

$$\begin{aligned} S &\sim d_I \\ f &\sim d_I^{-n} \\ v &\sim d_I^{-2} \\ A &\sim d_I^{2} \end{aligned} \tag{5}$$

Therefore, the frictional pressure drop during the test, Δp_F, can be related to the initial pressure drop at the beginning of the test, Δp_{F0}, with the following equation,

$$\Delta p_F = \Delta p_{F0}\left(\frac{d_I}{d_I - 2\delta_W}\right)^{5+n} \tag{6}$$

Obviously, there is a very strong relationship between the pressure drop and the change in the pipe diameter. Comparably, other effects may well be negligible. The wax thickness can be calculated

$$\delta_W = 0.5 d_I\left[1-\left(\frac{\Delta P_{F0}}{\Delta P_F}\right)^{\frac{1}{5+n}}\right] \tag{7}$$

This reasoning is also valid for other flow patterns. For instance, the above equation can be used for slug flow if we assume that the slug characteristics do not changes during wax deposition. Figure 3.6 shows the wax thickness calculated with the pressure drop method for a horizontal slug flow test using South Pelto Oil (Matzain[1]). This horizontal slug flow test had a superficial oil velocity of 4 ft/s and a superficial gas velocity of 5 ft/s. The large fluctuations are due to the pressure drop fluctuations of the slug flow. Smoother curves can be obtained by averaging the thickness across a 10 minute duration.

The pressure drop method is not successful for vertical multiphase flow, when the frictional pressure drop is only a small portion of the total pressure (due to the large gravitational pressure drop). The differential pressure transducer can not give a reliable frictional pressure drop measurement.

Table 3.12 lists the errors in deposit thickness δ_w for different values of the differential pressure ΔP. From Table 3.13 it is obvious that, at low flow rate (*e.g.* 2 ft/s corresponding to about 3 in. H_2O of differential pressure), measurement of the wax thickness may not be reliable. Therefore, the pressure drop method is not applicable at low flow rate situations, especially laminar flow.

- ***Heat Transfer Method***

The heat transfer method can be used for measurement of wax thickness if we assume that the heat transfer reduction is caused only by the insulation effect of the wax layer and the other flow and heat transfer conditions remain the same. Then, the wax thickness can be calculated as

$$\delta_W = r_I\left(1-\exp\left[\frac{2\pi k_W L}{C_P \rho Q}\left(\frac{\Delta T_{A0}}{\Delta T_{B0}} - \frac{\Delta T_A}{\Delta T_B}\right)\right]\right) \tag{8}$$

where k_W is the thermal conductivity of the wax layer, L is the length of test section, ΔT_A is the temperature difference between inside and outside of the pipe, ΔT_B is the temperature difference between inlet and outlet of the test section. The total heat flow rate consists of the heat flow rates of oil and gas,

$$C_P \rho Q = C_{PO}\rho_O Q_O + C_{PG}\rho_G Q_G \tag{9}$$

An error margin of +/- 0.11 mm was estimated when the difference between the inlet and outlet oil temperature was 2.2 °C (4 °F) with a confidence of 95%. If the value in the deposit thickness δ_w changes from 0.1 to 1 mm, its

relative error changes from ±110% to ±11%. For turbulent flow cases this measurement may not be accurate enough, since the temperature difference between the inlet and the outlet of each segment may be small. The error analysis indicates that the heat transfer method may not be reliable to give an accurate measurement of the wax thickness because of the small difference between the inlet and outlet oil temperature, and the uncertainty of the thermal conductivity of the wax deposit.

iv. Repeat Tests Results

The following tests were the tests run with the new startup procedure and the slightly lower ΔT of 42 °F.

- ***Annular Flow-Horizontal (WAX2003-018)***

This test is an annular horizontal flow test with superficial oil and gas velocities of 0.2 ft/s and 30 ft/s respectively. This test was a repeat of test WAX2002-010 with same oil and gas superficial velocities.

The deposit thicknesses from online LD-LD and offline LD-LD devices were 0.5 mm and 0.8 mm respectively. These compared well with the original test (WAX2002-010) results of 0.3 mm and 0.9 mm for online and offline LD-LD, respectively. The offline LD-LD is expected to give a slightly higher deposit because the spool piece is located at the end of the test section while the online LD-LD averages the thickness in the first part of the test section.

The inspection of the spool piece showed that there was less deposit on the top part of the pipe compared to the bottom of the pipe. Even some places at the top part did not have wax deposit at all. The wax deposit was medium hard and brown. The deposit was not very smooth and not uniformly distributed along the pipe wall.

Since oil superficial velocity is so small and gas superficial velocity is very high, it was very hard to control the flow rates during the steady state condition.

The wax thickness from the temperature data was calculated with a thermal conductivity of wax 1.5 times greater than that of the oil ($k_{wax}=1.5k_{oil}$). The fluctuations in the thickness are the direct results of fluctuations in the gas and oil velocities. The thickness calculated from the temperature data can only be compared with the online LD-LD since the temperatures are measured at the inlet and outlet of the test section.

Fluctuations in flow rates caused fluctuations in pressure drop data, so thickness calculations could not be done from pressure drop method for this test.

- ***Annular Flow-Horizontal (WAX2003-039)***

After seeing the fluctuations in the flow rates and the thickness plot from heat transfer method, WAX2003-018 was repeated one more time. This test is the third repeat of WAX2002-010. Superficial oil and gas velocities are 0.2 ft/s and 30 ft/s respectively. The deposit thickness from offline and on-line LD-LD was 1.3 mm and 0.5 mm respectively.

The boroscope picture of the deposit on the spool piece is shown in Fig. 3.7. The same behavior was observed with previous two experiments; there was less deposit at the top part of the spool piece and some part of the spool piece did not have deposit at all. The deposit was medium hard, brown and not uniformly distributed along the pipe. Also, there were big gas bubbles on the deposit. However, previous South Pelto crude oil multiphase tests run under the same flow rates produced uniform deposit circumferentially along the pipe as it could be expected from an annular flow test.

The oil concentration in the wax deposit for the spool piece was 68%, and for the test section pipe 60%.

The wax thickness from the temperature data was calculated with a thermal conductivity of wax equal to that of the oil ($k_{wax}=k_{oil}$). Although the fluctuations in the heat transfer thickness calculation plot were reduced compared to those in WAX2003-018, they still

can be seen in the thickness graph as a result of fluctuations in the gas and oil velocities.

Overall those three repeat tests WAX2003-018 and WAX2003-039 gave similar online and offline LD-LD results as test WAX2002-010 which was run under the same conditions with slightly different procedures.

The pressure drop method could not give any meaningful result because of fluctuations in pressure drop data.

- ***Intermittent Flow-Vertical (WAX2003-020):***

Test WAX2003-020 was an intermittent vertical flow test with superficial oil and gas velocities of 0.5 ft/s and 1 ft/s respectively. The deposit thickness was 1.6 mm from both offline and online LD-LD's. This test was repeat test of WAX2003-006 which was run at the same flow rate conditions. The online and offline LD-LD results from original test WAX2003-006 were 1.1 mm and 1.9 mm respectively.

A boroscope picture of the deposit on the spool piece is shown in Fig. 3.8. The deposit was medium hard, dark yellow and uniformly distributed on the pipe surface.

Oil concentrations in the wax deposits of the spool piece and pipe were 76% and 63% respectively.

The wax thickness was calculated from the temperature data using a thermal conductivity multiplier of 1.5 ($k_{wax}=1.5k_{oil}$). Nearly 17 hours later, calculations gave a sudden decrease in deposit thickness. For the first 17 hours, superficial gas velocity was fluctuating around 1.2 to 1.3 ft/s, after 18 hours, control of superficial gas velocity of 0.99 to 1.0 ft/s was achieved. However, change in velocity caused a decrease in inlet oil temperatures; therefore thickness calculation method gave less deposit than LD-LD results.

- ***Intermittent Flow-Vertical (WAX2003-023)***

WAX2003-023 was a repeat test of WAX2002-014 which also a vertical test conducted under intermittent flow conditions. The superficial oil velocity was 2 ft/s and the superficial gas velocity was 3 ft/s. The wax thicknesses obtained from offline LD-LD was 0.6 mm. Online LD-LD could not be performed because of some gauge problems. The wax thicknesses from WAX2002-014 were 0.3 mm from online LD-LD and 0.5 mm from offline LD-LD.

From the inspection of the spool piece, the wax deposit thickness was very thin on the pipe surface. It was observed that the deposit was hard and light brown. The deposit was uniformly distributed along the pipe wall as we can see from the boroscope picture of the deposit on the spool piece shown in Fig. 3.9.

The wax thickness was calculated from the temperature data for thermal conductivity multiplier of 2 ($k_{wax}=2k_{oil}$). Since the thickness was so small, the heat transfer method could not produce very reliable results. Even though the thermal conductivity of wax was set as twice of that of the oil, there was still large difference between thicknesses from LD-LD's and temperature calculations; we should also note that thicknesses are very small and within the error band for the online LD-LD (+/-0.2mm). Therefore real average deposit thickness in the test section could be smaller than the offline LD-LD result from the spool piece.

- ***Annular Flow-Vertical (WAX2003-034)***

The other vertical repeat test WAX2003-034 was run to study the paraffin deposition process for annular flow conditions with a low superficial oil velocity of 0.5 ft/s and high superficial gas velocity of 20 ft/s. The deposit thickness from offline LD-LD was 1.3 mm and the deposit thickness was 0.9 mm from online LD-LD. The original test WAX2002-018 was run under same flow rate conditions. The deposit thickness for WAX2002-018 was 0.9 mm from offline LD-LD.

After shutdown, the removable spool piece was inspected. The deposit was brown and medium hard and uniformly distributed on the spool piece (axially and radially). The boroscope pictures of the deposit found on the spool piece are shown in Fig. 3.10.

The oil concentration in the wax deposit was 60% in the spool piece and was 51 % on the test section pipe.

In the wax thickness calculations from the temperature data, the thermal conductivity of wax was assumed to be 1.5 times of the oil thermal conductivity (kwax=1.5 koil). The overall thickness result from temperature data was in a good agreement with online LD-LD result.

- ***Annular Flow-Vertical (WAX2003-035)***

WAX2003-035 was a vertical annular flow test in the original test matrix. This test was only run with new startup procedure and ΔT of 42ºF. The superficial oil and gas velocities were 0.5 ft/s and 30 ft/s respectively. After 24 hours, the deposit thickness from offline LD-LD measurement was 1.0 mm and from online LD-LD was 0.8 mm.

After shutdown the spool piece at the end of the test section was studied. A light brown deposit was found on the spool piece. The deposit was medium-hard and uniformly distributed on the pipe surface. There were also large gas bubbles on the deposit surface. The boroscope pictures of the deposit on the spool piece are shown in Fig. 3.11.

The trapped oil concentration in the wax deposit in the pipe was 50 % while the one from the spool piece was 46 %.

The wax thickness was also calculated from the temperature data by setting the thermal conductivity of the wax equal to two times of the oil thermal conductivity ($k_{wax}=2k_{oil}$). The fluctuations in the thickness come from the fluctuations in gas flow rates and glycol temperatures. The comparison between offline LD-LD and temperature calculation results show that thicknesses from those methods agree (0.8 mm and 1.0 mm respectively).

- ***Annular Flow-Vertical (WAX2003-036)***

Last annular flow vertical test WAX2003-036 was a repeat test of WAX2002-015 run with the old start-up procedure and a ΔT of 45ºF. The superficial oil and gas velocities were 4 ft/s and 30 ft/s respectively. After 24 hours, the deposit thickness from offline LD-LD measurement was 0.2 mm and from online LD-LD was 0.3 mm. The thicknesses from WAX2002-015 were again 0.2 mm and 0.3 mm from offline and online LD-LD respectively.

After shutdown the spool piece at the end of the test section was studied. A brown deposit was found on the spool piece. The deposit thickness was very thin and there were big gas bubbles on the deposit surface. The deposit was hard and uniformly distributed on the pipe surface. The boroscope picture of the deposit on the spool piece is shown in Fig. 3.12.

The trapped oil concentration in the wax deposit in the pipe was 59 % while the one from the spool piece was 57 %.

v. Summary of Results

The test matrices for the multiphase loop with Garden Banks Condensate in horizontal and vertical flow patterns were completed. In addition to those tests, 8 additional repeat tests were run with new start-up procedure and ΔT of 42°F. The results for those 24-hour tests done in the multiphase flow loop with Garden Banks condensate are summarized in Table 3.14. The tests in bold characters were run with the new procedures.

The two-phase flow experiments have shown that the deposit thicknesses are flow pattern dependent. Figures 3.13 and 3.14 show all deposit patterns on the horizontal and vertical flow pattern maps.

For horizontal flow, the thickest deposit was produced from the annular flow experiment. Average deposit thickness of around 0.3 mm was obtained from both online and offline LD-LD for three intermittent flow and one stratified smooth experiments. Stratified smooth and stratified wavy gave soft deposits and stratified wavy gave a slightly thicker deposit than stratified smooth flow.

For vertical flow, high superficial oil velocities gave lower deposit thicknesses. Bubbly flow and one of the annular flow tests with a high superficial oil velocity produced the

thinnest deposit. For intermittent vertical flow tests and lower oil superficial velocity, the deposit thickness was very high compared to the rest of thicknesses from all the tests. Increases in oil superficial velocity resulted in lower deposit thicknesses for vertical flow.

- ***Comparisons between Horizontal and Vertical Flow Tests***

Most tests yielded deposits around 0.2 to 0.4 mm. Annular flow tests with oil velocity below 1 ft/s gave deposits around 0.8-1.0 mm. Higher oil velocity in vertical flow resulted in a thinner deposit in annular flow (0.2-0.3mm).

Similarly, vertical intermittent flow tests with oil velocities below 1 ft/s yielded large deposits (more than 1 mm). Higher oil velocities (above 1 ft/s) in vertical intermittent flow yielded much thinner deposits similar to those obtained in horizontal flow with oil velocities above 1 ft/s.

- ***Comparison between Single-Phase and Multiphase Tests***

On the multiphase loop, four horizontal single-phase tests were run with Garden Banks condensate but three of them were run with a temperature difference of 30 ºF between oil and glycol-water mixture. Therefore only one horizontal single-phase test could be compared. WAX2002-005 was a 48-hour test with a superficial oil velocity of 3.4 ft/s and ΔT of 45 ºF. That test is shown in Table 3.15.

Horizontal two-phase tests with a superficial oil velocity of 4 ft/s yielded the deposit thickness around 0.3 mm. This is comparable with the horizontal single-phase test which produced the deposit thickness of 0.4 mm. All intermittent horizontal multiphase flow tests with a superficial oil velocity of 4 ft/s produced the deposit thickness of 0.3 mm for a wide range of superficial gas velocities.

vi. Comparisons between Fluids

Comparisons between South Pelto and Garden Banks tests run at similar multiphase flowing conditions are given in Table 3.16. The South Pelto oil produced thicker deposits than the Garden Banks condensate with the exception of the vertical intermittent tests. For those tests, the Garden Banks condensate produced a thicker deposit than the South Pelto crude oil. The produced deposits from South Pelto were harder than those of Garden Banks.

Comparisons could not be performed in the stratified flow pattern since the thicknesses for South Pelto tests were not available.

The vertical annular flow test with a superficial oil velocity of 0.5 ft/s and a superficial gas velocity of 30 ft/s was an additional test for Garden Banks condensate. This test was added to the test matrix to make sure that the flow conditions would be completely in the annular flow region. There are no equivalent South Pelto tests to be compared to.

- ***Horizontal Multiphase Tests Comparisons***

Figure 3.15 shows all the deposit thicknesses for all South Pelto horizontal tests on the horizontal flow pattern map.

The comparisons between Garden Banks and South Pelto for different flow regimes in horizontal flow can be summarized as follow:

Intermittent Flow

For both Garden Banks and South Pelto fluids, tests with identical oil superficial velocity (4 ft/s) yielded similar deposits for a wide range of superficial gas velocities. South Pelto deposits were thicker than Garden Banks deposits. The nature of deposits for these tests was either hard or medium hard for both fluids.

Stratified Smooth and Wavy Flow

For Garden Banks, stratified wavy flow gave a thicker deposit than stratified smooth flow. Since the deposit thicknesses could not be measured for South Pelto, we could not compare them with the Garden Banks results. The deposits obtained from both fluids were comparable (soft or medium soft).

Annular Flow

In horizontal flow, the annular flow pattern produced the thickest deposits for both fluids

(0.9 to 1.3 mm from Garden Banks and 1.8 mm from South Pelto from offline LD-LD results). The deposits were medium hard and hard for Garden Banks South Pelto.

♦ ***Vertical Multiphase Tests Comparison***

Figure 3.16 shows all the deposit thicknesses for all South Pelto vertical tests on the vertical flow pattern map.

The comparison between Garden Banks and South Pelto for different flow regimes in vertical flow is as follows:

Intermittent Flow

Intermittent flow regimes produced the thickest deposit in vertical flow with both fluids (1 mm or larger). For these tests, the Garden Banks fluid produced a thicker deposit than South Pelto. However, at superficial oil velocities above 1 ft/s, the Garden Banks fluid produced a much thinner deposit while the South Pelto deposit remained around 1mm. The deposits were either hard or medium hard and comparable for both fluids.

Bubbly flow and Annular Flow

The average deposit thickness obtained from bubbly flow test for Garden Banks was around 0.30 mm and for South Pelto was around 0.55 mm (average of online and offline LD-LD). The deposits were medium hard and hard for Garden Banks and South Pelto bubbly flow respectively.

For the bubbly flow test and one of the annular flow tests with a superficial oil velocity of 4 ft/s, the produced deposits were thinner than those obtained from other flow types regardless of the superficial gas velocity (0.5 ft/s for bubbly and 30 ft/s for annular). For the other annular tests, offline LD-LD gave an average thickness of around 0.9 mm for Garden banks and South Pelto.

The superficial oil velocity seems to be an important governing parameter in the deposition process. More tests should be conducted to study the effect of the oil velocity and gas velocities respectively for different flow patterns.

The deposits for annular tests were medium hard for both fluids.

vii. Conclusions:

- A total of 21 multi-phase tests were conducted in the multiphase flow loop using Garden Banks crude oil. Both horizontal and vertical flow test matrixes were completed. Also 8 repeat tests were conducted with new operating procedures.

- Garden Banks Horizontal flow tests:
  - Annular flow tests produced the thickest deposits.
  - Intermittent and stratified smooth produced thinner deposits of comparable values.
  - Stratified wavy produced thicker deposits than stratified smooth flow
- Garden Banks Vertical flow tests:
  - Bubbly flow and annular flow tests with high superficial oil velocities produced the thinnest deposits.
  - Intermittent flow tests with low superficial oil velocities produced the thickest deposit thickness.
  - Increase in oil superficial velocity results in thinner deposits.
- South Pelto deposition tests run under similar conditions produced thicker deposits, except for the intermittent vertical flow tests.
- The thickness calculations from heat transfer methods give good results compared to the results of online and offline LD-LD. The heat transfer method has an error band of +/- 0.11 mm with a confidence of 95%. If the value in the deposit thickness δ_w changes from 0.1 to 1 mm, its relative error changes from ±110% to ±11%.
- The thickness calculations from pressure drop measurements match with the measured thicknesses for the horizontal flow tests for South Pelto oil. Because there were fluctuations in the pressure data from the original Garden Banks horizontal flow tests, the pressure drop method did not yield any meaningful results. Also, if the thickness was too thin to yield significant change in

the pressure drop, then pressure drop measurements can not be used. The thickness calculations from pressure drop measurements did not work for the vertical flow tests due to the predominance of the gravitational term in the total pressure measurement. The same problem was encountered with the South Pelto vertical test results. The predicted frictional pressure gradient compared to the total (or gravitational) pressure gradient was very small and the falling film friction overtakes the slug body friction.

- Most reliable methods for thickness calculations are from the online LD-LD and offline LD-LD. Online LD-LD has an error band of +/- 0.2 mm and the offline LD-LD gives results within +/- 0.025 mm with a 95% confidence interval for deposits around 1mm. However, if the thickness of the deposit changes from 1 to 0.1 mm, the relative error band increases from ±2.5% up to ±25%.
- Results of repeat tests produced very good agreements in overall thickness results from both online and offline LD-LD even though start-up method and ΔT were slightly changed. Therefore early deposition did not effect on the overall thickness results.

viii. Future Work

- South Pelto and Garden Banks will continue to be analyzed and compared, especially the wax content measurements from DSC results.
- Two additional vertical tests will be run with Garden Banks Condensate to investigate the effect of the oil superficial velocity. The test conditions were given in Table 3.17.

Table 3.9 - Summary of the Garden Banks Condensate Tests on the Multiphase Loop.

Refence Number	Vsl (ft/s)	Vsg (ft/s)	Position	Flow Regime	Start-up Procedure	ΔT (°F)
WAX2002-008	4.0	5.0	Horizontal	Intermittent	Old Procedure	45
WAX2002-009	4.0	15.0	Horizontal	Intermittent	Old Procedure	45
WAX2002-010	0.2	30.0	Horizontal	Annular	Old Procedure	45
WAX2002-011	0.2	7.0	Horizontal	Stratified Wavy	Old Procedure	45
WAX2002-012	0.2	1.0	Horizontal	Stratified Smooth	Old Procedure	45
WAX2002-013	4.0	1.0	Horizontal	Intermittent	Old Procedure	45
WAX2002-014	2.0	3.0	Vertical	Intermittent	Old Procedure	45
WAX2002-015	4.0	30.0	Vertical	Annular	Old Procedure	45
WAX2002-018	0.5	20.0	Vertical	Annular	Old Procedure	45
WAX2003-003	4.0	0.5	Vertical	Bubbly	Old Procedure	45
WAX2003-006	0.5	1.0	Vertical	Intermittent	Old Procedure	45
WAX2003-007	0.5	4.0	Vertical	Intermittent	Old Procedure	45
WAX 2003-014 (REPEAT WAX2003-007)	0.5	4.0	Vertical	Intermittent	New Procedure	42
WAX2003-015 (REPEAT WAX2002-008)	4.0	5.0	Horizontal	Intermittent	New Procedure	42
WAX2003-018 (REPEAT WAX2002-010)	0.2	30.0	Horizontal	Annular	New Procedure	42
WAX2003-020 (REPEAT WAX2003-006)	0.5	1.0	Vertical	Intermittent	New Procedure	42
WAX2003-023 (REPEAT WAX2002-014)	2.0	3.0	Vertical	Intermittent	New Procedure	42
WAX2003-034 (REPEAT WAX2003-018)	0.5	20.0	Vertical	Annular	New Procedure	42
WAX2003-035	0.5	30.0	Vertical	Annular	New Procedure	42
WAX2003-036 (REPEAT WAX2002-015)	4.0	30.0	Vertical	Annular	New Procedure	42
WAX2003-039 (REPEAT WAX2003-018)	0.2	30.0	Horizontal	Annular	New Procedure	42

Table 3.10 – Original Horizontal Multiphase Test Matrix for Garden Banks Condensate

Test #	Flow Pattern	v_{SL}	v_{SG}
1	Stratified Smooth	0.2	1.0
2	Stratified Wavy	0.2	7.0
3	Annular	0.2	30.0
4	Intermittent	4.0	1.0
5	Intermittent	4.0	5.0
6	Intermittent	4.0	15.0

Table 3.11 - Vertical Multiphase Test Matrix for Garden Banks Condensate

Test #	Flow Pattern	v_{SL}	v_{SG}
1	Intermittent	0.5	1.0
2	Intermittent	0.5	4.0
3	Intermittent	2.0	3.0
4	Annular	0.5	20.0
5	Annular	0.5	30.0
6	Annular	4.0	30.0
7	Bubbly	4.0	0.5

Table 3.12 - Dependence of Deposit Thickness δ_w Error on Value of ΔP

ΔP (in. H_2O)	Error of the deposit thickness δ_w (±mm)
3	0.28
6	0.14
12	0.07
24	0.035
48	0.018
96	0.009

Table 3.13 - Dependence of Deposit Thickness δw Error on Value of ΔT

T_{in}-T_{out} (°F)	Error of the deposit thickness δ_w (±mm)
1	0.44
2	0.22
4	0.11
8	0.055

Table 3.14 - Summary of Multiphase Tests with Garden Banks Condensate

Test #	Vsl, ft/s (m/s)	Vsg ft/s (m/s)	ΔT (°F)	ReL	ReG	Position	Flow Regime	Online LD-LD (mm)
WAX2002-008	4 (1.22)	5 (4.57)	45	15945	98723	HORIZ	INT	-
WAX2002-009	4 (1.22)	15 (4.57)	45	15945	296186	HORIZ	INT	0.3
WAX2002-010	0.2 (0.06)	30 (9.14)	45	797	592373	HORIZ	ANN	0.3
WAX2002-011	0.2 (0.06)	7 (2.13)	45	797	138220	HORIZ	SW	0.6
WAX2002-012	0.2 (0.06)	1 (0.31)	45	797	19746	HORIZ	SS	0.3
WAX2002-013	4 (1.22)	1 (0.31)	45	15945	19746	HORIZ	INT	0.3
WAX2002-014	2 (0.61)	3 (0.91)	45	7973	59237	VERT	INT	0.3
WAX2002-015	4 (1.22)	30 (9.14)	45	15945	592373	VERT	ANN	0.2
WAX2002-018	0.5 (0.15)	20 (6.10)	45	1993	394915	VERT	ANN	-
WAX2003-003	4 (1.22)	0.5 (0.15)	45	15945	9873	VERT	BUB	0.3
WAX2003-006	0.5 (0.15)	1 (0.31)	45	1993	19746	VERT	INT	1.1
WAX2003-007	**0.5 (0.15)**	**4 (1.22)**	**45**	**1993**	**78983**	**VERT**	**INT**	**1.2**
WAX2003-014 (REPEAT WAX2003-007)	**0.5 (0.15)**	**4 (1.22)**	**42**	**1993**	**78983**	**VERT**	**INT**	**1.1**
WAX2003-015 (REPEAT WAX2002-008)	**4 (1.22)**	**5 (4.57)**	**42**	**15945**	**98723**	**HORIZ**	**INT**	**0.3**
WAX2003-018 (REPEAT WAX2002-010)	**0.2 (0.06)**	**30 (9.14)**	**42**	**797**	**592373**	**HORIZ**	**ANN**	**0.5**
WAX2003-039 (REPEAT WAX2003-018)	**0.2 (0.06)**	**30 (9.14)**	**42**	**797**	**592373**	**HORIZ**	**ANN**	**0.5**
WAX2003-020 (REPEAT WAX2003-003)	**0.5 (0.15)**	**1 (0.31)**	**42**	**1993**	**19746**	**VERT**	**INT**	**1.6**
WAX2003-023 (REPEAT WAX2002-014)	**2 (0.61)**	**3 (0.91)**	**42**	**7973**	**59237**	**VERT**	**INT**	**-**
WAX2003-034 (REPEAT WAX2002-018)	**0.5 (0.15)**	**20 (6.10)**	**42**	**1993**	**394915**	**VERT**	**ANN**	**0.9**
WAX2003-035	**0.5 (0.15)**	**30 (9.14)**	**42**	**1993**	**592373**	**VERT**	**ANN**	**0.8**
WAX2003-036 (REPEAT WAX2002-015)	**4 (1.22)**	**30 (9.14)**	**42**	**15945**	**592373**	**VERT**	**ANN**	**0.2**

Table 3.15 - Horizontal Single-Phase Tests with Garden Banks on the Multiphase Loop

Test#	To (ºF)	ΔT (ºF)	Duration	Vsl (ft/s)	Qo (BPD)	Re	Online LD-LD
WAX2002/005	85	45	48	3.36	1210	13395	-

Table 3.16 - Garden Banks and South Pelto Crude Oil Multiphase Flow Loop Results

				Garden Banks Condensate	South Pelto Crude Oil
Vsl (ft/s)	Vsg (ft/s)	Position	Flow Regime	Online LD-LD (mm)	Online LD-LD (mm)
4	5	Horizontal	INT	- 0.2	0.5
4	15	Horizontal	INT	0.3	0.5
0.2	30	Horizontal	ANN	0.3 0.5 0.5	1.4
0.2	7	Horizontal	SW	0.6	-
0.2	1	Horizontal	SS	0.3	-
4	1	Horizontal	INT	0.3	0.7
2	3	Vertical	INT	0.3 -	1.1
0.5	1	Vertical	INT	1.1 1.6	0.9
0.5	20	Vertical	ANN	- 0.9	0.7
0.5	30	Vertical	ANN	0.8	-
4	0.5	Vertical	BUB	0.3	0.6
0.5	4	Vertical	INT	1.2 1.1	0.9
4	30	Vertical	ANN	0.2 0.2	0.6

Table 3.17 - Additional Intermittent Multiphase Flow Tests with Garden Banks Condensate

Test #	Vsl, ft/s (m/s)	Vsg ft/s (m/s)	ΔT (ºF)	ReL	ReG	Position	Flow Regime
WAX2003-047	1 (0.31)	4 (1.22)	42	19746	15945	VERT	INT
WAX2003-048	2 (0.61)	1 (0.31)	42	7973	19746	VERT	INT

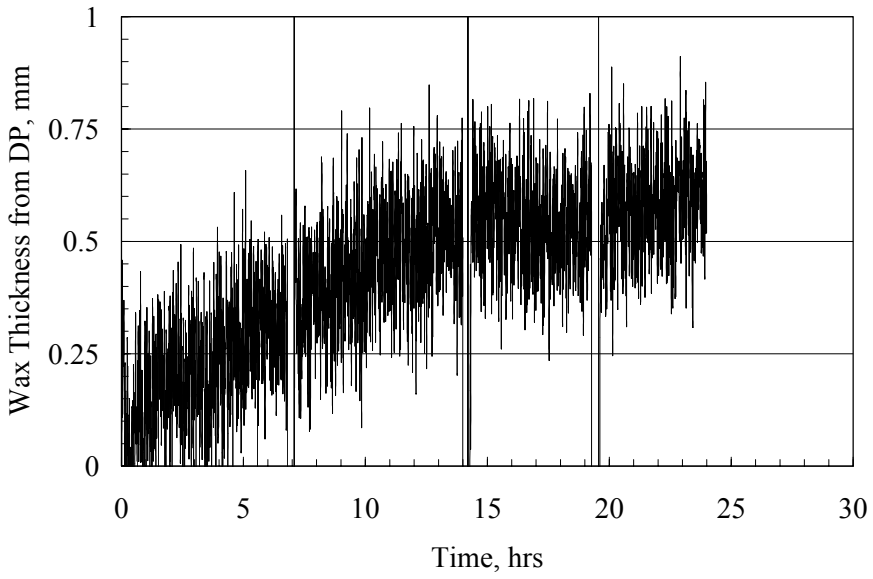


Figure 3.6 - Wax Thickness Calculated from Pressure Drop (South Pelto Oil, Horizontal Slug Flow)

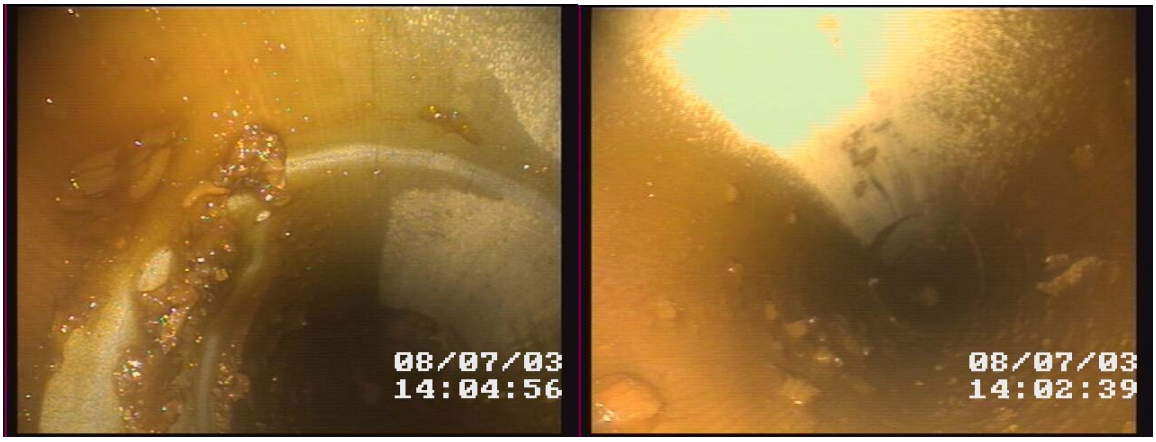


Figure 3.7 - View of Scrapes on the Deposit Surface (WAX2003-039).

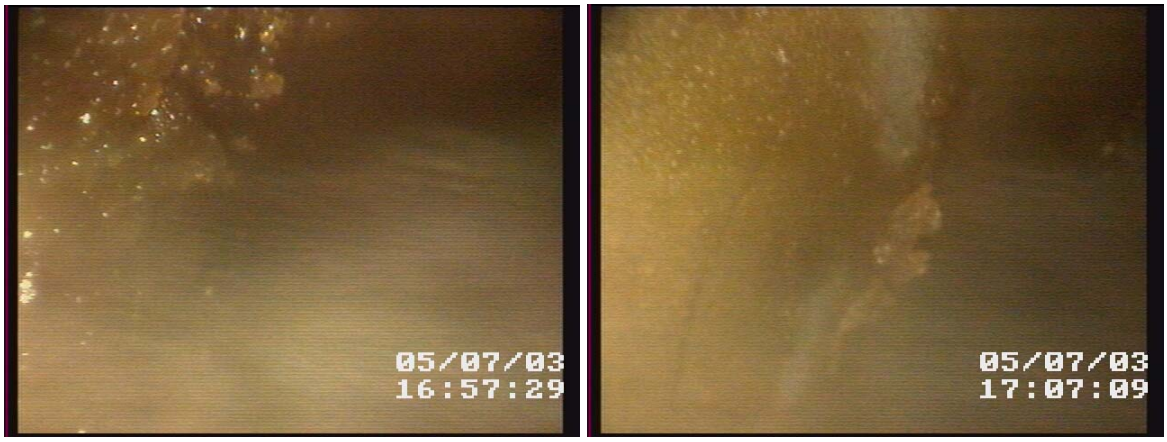


Figure 3.8 - View of Scrape on the Deposit Surface (WAX2003-020)

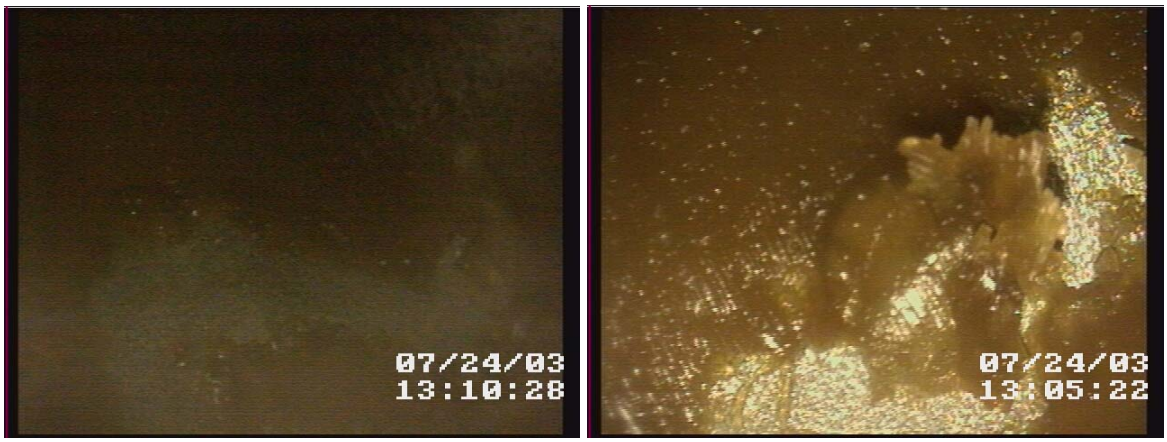


Figure 3.9 - View of Scrape on the Deposit Surface (WAX2002-023).

Figure 3.10 - View of Scrape on the Deposit Surface (WAX2003-034)

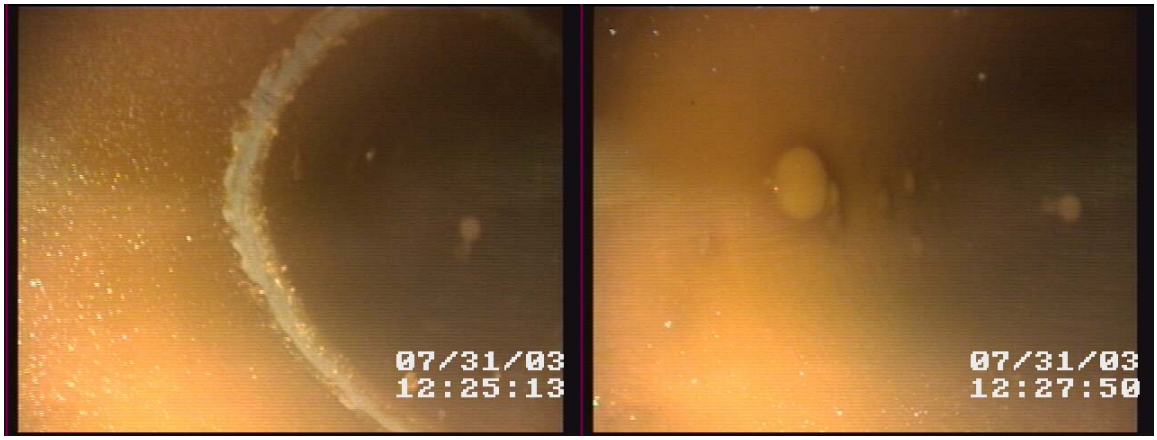


Figure 3.11 - View of a Scrape on the Deposit Surface (WAX2003-035)

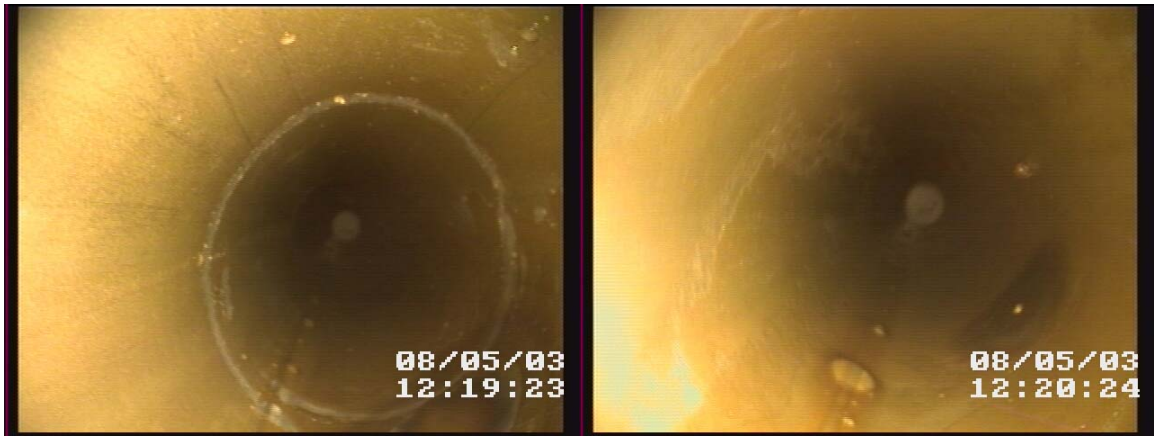


Figure 3.12 - View of a Scrape on the Deposit Surface (WAX2002-036)

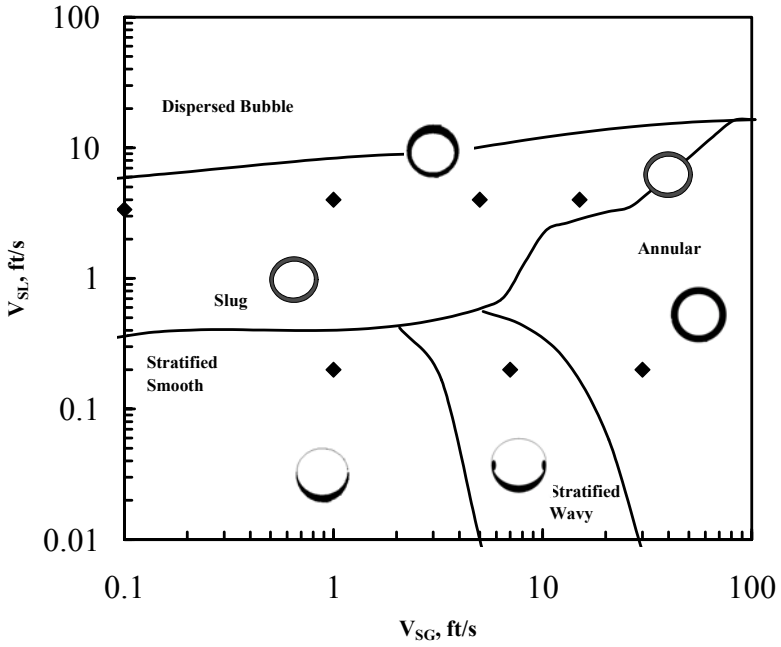


Figure 3.13 - Garden Banks Condensate and Tulsa City Gas at 350 psi, 85°F and 0 deg in a 2-in Pipe

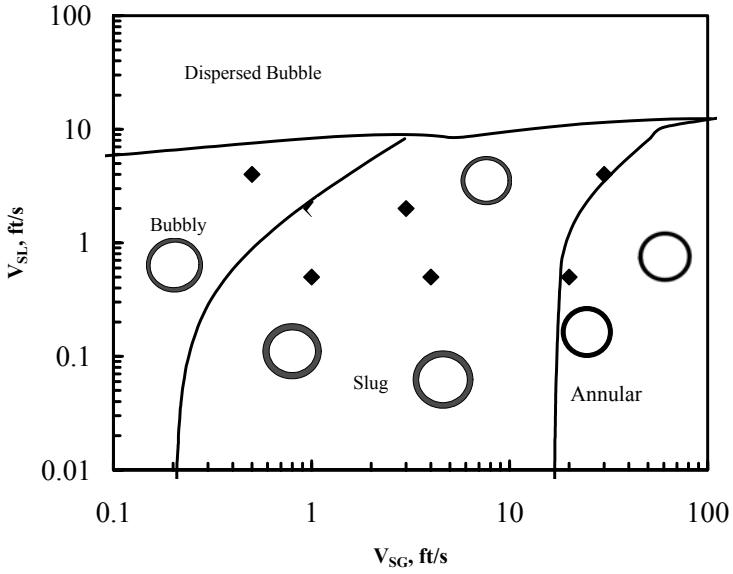


Figure 3.14 - Garden Banks Condensate and Tulsa City Gas at 350 psi, 85° and 90 deg in a 2-in Pipe.

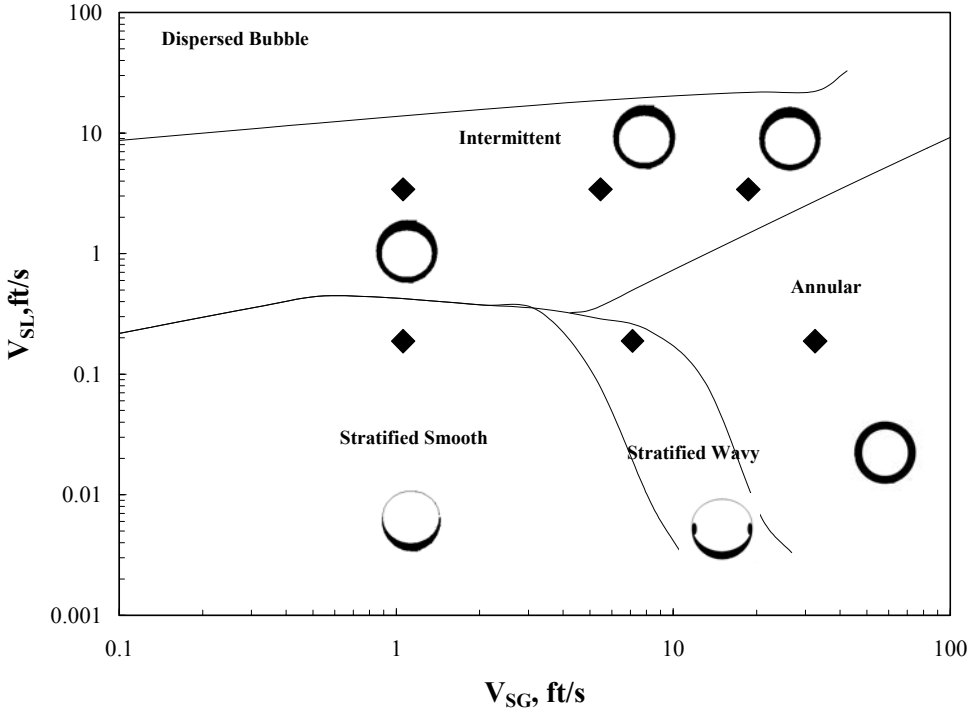


Figure 3.15 - South Pelto and Tulsa City Gas at 350 psi, 105°F and 0 deg in a 2-in Pipe

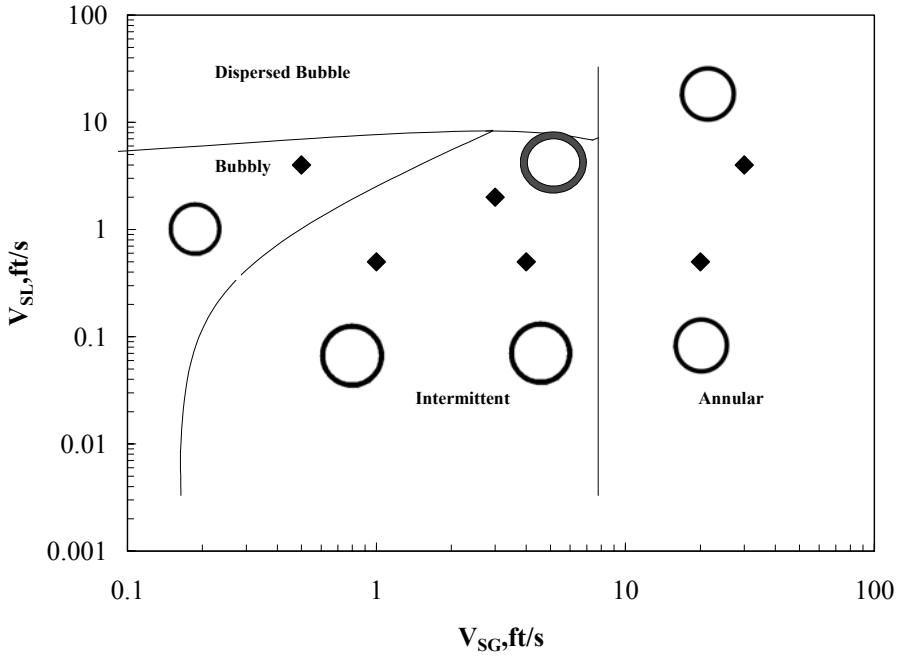


Figure 3.16 - South Pelto and Tulsa City Gas at 350 psi, 105°F and 90 deg in a 2-in Pipe

d. Three-Phase Studies

i. Experimental Procedure

First, the temperatures of the baths are set according to the test condition. The hot bath is set 15° F below the cloud point of the oil, while the cold bath is set according to the desired ΔT for the test. When the baths reach the said temperatures, the oil that had been heated overnight is poured into beakers which are already in the cold finger bath. The cold finger probes are then placed in the beakers and the rotational stirrer is set to the desired speed.

After the test is finished, the probes are removed from the bath and allowed to dry for approximately thirty minutes. Three wax samples are then taken directly from each probe, weighted and later analyzed by the DSC. The deposited wax is collected on paper towels and weighed. With this procedure, the trapped oil in the deposit can be absorbed by the paper towels and result in a bias in the DSC results. Therefore, a new procedure recently adopted by Nalco is now followed. This procedure consists of setting the temperature of the glycol to about 30° F above the cloud point of the oil and this hot water is circulated through the cold finger probes. The wax is melted, collected in small cups and sampled for DSC analyses. The remaining wax on the probes is then removed with a paper towel and weighed as before. This new procedure is being used from Test 17 onwards.

For two-phase oil-water tests, the procedure is the same, except that the emulsions are prepared in the beakers before placing them in the cold finger bath. A mixer speed of 600 rpm for a period of 2 minutes is used to prepare the emulsions.

ii. Cold Finger Deposition Test Matrix

A series of cold finger tests have been run since the last ABM. Three different types of tests have been conducted:

- Commissioning and calibration tests, to verify the operation of the device and repeatability of the results.
- Single-phase tests with a focus on the effect of ΔT.
- Preliminary oil/water test to investigate the effect of water .

The test conditions common for all these tests were:

Crude Oil: South Pelto
Oil Temperature: 105° F
Rotational Speed: 500 rpm
Period: 24 hours, except for test 12, which was 48 hours long.

Table 3.18 shows the test matrix for the commissioning tests.

Tests 2, 3 and 4 were run before the flow meters were installed and large discrepancies in the data were observed between the cells. These discrepancies were identified as coming from varying glycol flow rates between each cell. Flow meters have been installed from test 5 and onward to correct this problem.

After verifying proper operation of the cold finger device, single-phase tests were run (tests 14, 15 and 16) to investigate the effect of ΔT. The temperature differences between the oil and the cold finger were chosen to be 15°F, 30°F and 45° F, to be similar to the ΔTs used in the flow loop tests.

For each test, the deposit is weighed and a DSC analyses is run.

Table 3.19 shows the test matrix for the single-phase and oil-water tests.

For all of the two-phase tests, a 30g/l salt water solution was prepared. The oil and salt water were mixed in beakers with a mixer for 2 minutes at 600 rpm. The beakers were then placed in the cold finger device.

For the cold finger device with this geometry, the Reynolds number can be calculated with the following expression given by Weispfennig, (2001):

$$\mathbf{Re} = \frac{\frac{\rho \omega D_S D_{CF}}{2}}{\mu}$$

where:

ρ : density of the oil $\left(kg/m^3\right)$

ω : stirrer rotational speed $\left(s^{-1}\right)$

D_S : stirrer diameter (m)

D_{CF} : cold finger diameter (m)

μ : viscosity of the oil @ test temperature $\left(kg/m.s\right)$

For the South Pelto crude oil and our cold finger geometry, the calculated Reynolds number is about 1,200, which means all the tests are conducted in the laminar flow region.

iii. Experimental Results

Table 3.20 summarizes the results available for the deposition tests. These results are discussed below.

iv. Single-Phase Tests

For the single-phase tests, the deposits were all very soft, essentially like a gelled oil. The overall mass of the deposit increased as the ΔT increased, but the average wax fraction decreased.

For tests 15, in one of the four probes (cell C), the deposit sloughed off the cold finger immediately after they were taken out of the beakers (fig.3.17) and the weight could not be measured. For test 16, the deposits were visually much softer than the ones on tests 14 and 15. On all four probes, the deposits sloughed off the probes the same way as in test 15 (fig.3.18), but as this was anticipated, the deposit was not lost and its weight was measured. The higher oil contents combined with the heavier weight of the deposits is an explanation for the sloughing of the deposits in both tests 15 and 16.

Figure 3.19 shows the plots of weight versus temperature difference for tests 14, 15 and 16. A trend in weight as the temperature difference increases can clearly be seen by this plot for the four cells. For test 15, where ΔT = 30° F, cell C is the one in which the deposit sloughed off the probe. From the plot, this loss of deposit can be visualized by the sudden drop in weight between cells B and C, compared to the other two tests.

Figure 3.20 shows the change in wax content and weight of the deposits for the single-phase tests with South Pelto (tests 14, 15 and 16) as a function of ΔT. The results show an increase in the average weight of the deposits as the temperature difference increases, while the wax content decreases with an increase in ΔT.

v. Oil-Water Tests

Four tests with four different water cuts have been run with South Pelto crude oil. Test 17 had two cells running with 20% salt water and two with 40% salt water content. The amount of deposits for both water cuts, especially 40%, were less than the ones verified for single-phase tests at the same ΔT (test 14). Visually, the deposits obtained for single-phase test and 20% water cuts were very similar in thickness. For 40% water cuts, the deposits were very thin and not homogeneous around the probe.

At 20% water cuts, the average weight after 24 hours was 0.80 g of deposits. At 40% water cuts, the average weight was 0.58 g.

Figures 3.21 and 3.22 show the deposits for test 17 at both water cuts.

After allowing the deposits to dry, the temperatures in the cold finger probes were increased to above the cloud point of the oil and left overnight, to let the deposits melt, according to the new procedure described before. After 21 hours, a thin film could still be seen around the probes (Figures 3.23, 3.24). The film was then removed with a paper towel and weighed. This film that was removed was very hard and sticky, very similar to a candle wax.

Test 18 had two cells running with 60% salt water and two with 80% salt water content. During this test, both cells that contained 80% salt water stopped rotating at the very beginning of the test. Several attempts were made to restart them, but they always stopped rotating after reaching a certain rotational speed. Therefore, for test 18, only the cells with 60% water cuts were actually rotating at the desired test speed. The amount of deposits on each cell was considerably less than at the previous water cuts. For 60% water cuts, the average weight on each probe after 24 hours was 0.36 g of deposit. For 80% water cuts, the average weight was 0.28 g of deposit. Pictures of the cold finger probes were not taken. The deposits were, again, melted overnight. At 80% water cuts, this was enough to melt all the deposits around the cold finger probes. At 60% water cuts, a thin film similar to the ones verified in test 17 could still be seen.

Figures 3.25 and 3.26 show the cold finger probes after melting for both water cuts.

Test 19 had two cells running with 20% salt water and two with 40% salt water content. For 20% water cut, the average weight on each probe was 1.8 g of deposit; while for 40% the average weight was a little less, 1.2 g of deposit. After melting overnight, the thin film similar to the ones at the previous tests still could be seen, especially at 40% water cuts.

Test 20 had two cells running with 60% salt water and two with 80% salt water content. For 60% water cut, the average weight on each probe was 0.7 g of deposit, while for 80% the average weight was almost the same, 0.6 g of deposit.

Figure 3.27 gives the change in average weight of deposit for each water cut as function of ΔT. It can be seen that the amount of deposit decreases almost exponentially as the water cut increases. For a ΔT of 15°F, the average weight of deposits at 20% water cut is more than twice that at 80% water cut. For 30°F, the average weight of deposits at 20% WC is more than three times higher than at 80% water cut.

vi. Conclusions

For single-phase tests, an increase in the temperature difference between the cold finger probes and the bulk oil results in an increase in the amount of deposits and a decrease in the deposit wax contents.

As the ΔT increases, the ratio between weight and wax content increases, resulting in much softer deposits. The higher oil contents associated with the heavier weight of the deposits can be seen by the sloughing of the deposits on tests at higher ΔTs.

For two-phase tests, the amount of deposits is less than single-phase tests. Four different water cuts have been tested with South Pelto crude oil at different ΔTs. An increase in the water cut results in a decrease in the amount of deposits for the same ΔT.

Four different ΔT tests have been run for two-phase conditions. A behavior similar to single-phase conditions has been identified. As the ΔT increases, the amount of deposit increases at the same water cut.

vii. Future Work

After South Pelto tests results are completed, the CBI crude oil will be tested. Tests 23 to 25 will be run with the CBI crude oil to serve as single-phase tests baseline at a ΔT of 15, 30 and 45°F. Oil-water tests will be later run with 20%, 40%, 60% and 80% salt water contents over a period of 24 hours (tests 26 to 31).

The conditions for these tests will be:

Crude oil: CBI
Fluid Temperature: 85°F
Rotational Speed: 500 rpm
Period: 24 hours

After the completion of CBI tests, the aging tests are scheduled. Table 3.21 and 3.22 summarizes the planned test matrix for these aging tests with CBI and South Pelto, respectively.

Tests 32 to 36 will serve as a baseline with South Pelto single-phase oil tests, under

conditions typical of the deposition facilities. A total of 10 aging tests are expected to be run with South Pelto. Tests 37 to 41 are two-phase tests, with 20%, 40%, 60% and 80% salt water contents.

Tests 42 to 45 will serve as a baseline with CBI single-phase oil tests, under conditions typical of the deposition facilities. A total of 10 aging tests are expected to be run with CBI. Tests 47 to 51 are two-phase tests, with 20%, 40%, 60% and 80% salt water contents.

This cold-finger test matrix might be further expanded or modified based on the available test results. The Garden Banks condensate is also available for testing.

Table 3.18 - Commissioning Tests

Test #	Water	CF T (F)	ΔT
2	-	75	**30**
3	-	90	**15**
4	-	60	**45**
5	-	90	**15**
6	-	90	**15**
7	-	90	**15**
8	-	75	**30**
9	-	60	**45**
11	-	90	**15**
12	-	75	**30**
13		75	**30**

Table 3.19 – Single-Phase and Oil-Water Tests with South Pelto

Test #	Water Cut %	CF T (F)	ΔT (F)
14	0	90	**15**
15	0	75	**30**
16	0	60	**45**
17	20	90	**15**
	40	90	**15**
18	60	90	**15**
	80	90	**15**
19	20	75	**30**
	40	75	**30**
20	60	75	**30**
	80	75	**30**
21	20	60	**45**
	40	60	**45**
22	60	60	**45**
	80	60	**45**

Table 3.20 - Cold Finger Deposition Tests with South Pelto

Test #	Water Cut %	ΔT (° F)	Deposit Average Weight (g)	Deposit Average Wax Content (% weight)
14	0	15	1.3	17
15	0	30	3.2	8
16	0	45	4.0	7
17	20	15	0.8	14
	40	15	0.6	7
18	60	15	0.4	In Progress
	80	15	0.3	In Progress
19	20	30	1.8	In Progress
	40	30	1.2	In Progress
20	60	30	0.7	In Progress
	80	30	0.6	In Progress
21	20	45	In Progress	In Progress
	40	45	In Progress	In Progress
22	60	45	In Progress	In Progress
	80	45	In Progress	In Progress

Table 3.21 – Single-Phase and Two-Phase Tests

Test #	Water	CF T (F)	ΔT
23	0	70	**15**
24	0	55	**30**
25	0	40	**45**
26	20	70	**15**
	40	70	**15**
27	60	70	**15**
	80	70	**15**
28	20	55	**30**
	40	55	**30**
29	60	55	**30**
	80	55	**30**
30	20	40	**45**
	40	40	**45**
31	60	40	**45**
	80	40	**45**

Table 3.22 -Test Matrix for Aging Tests with South Pelto

Test #	Fluid	Water	ΔT	Hrs
032	SP	-	30	**3**
033	SP	-	30	**6**
034	SP	-	30	**12**
035	SP	-	30	**48**
036	SP	-	30	**60**
037	SP	20	30	**3**
	SP	40	30	**3**
038	SP	20	30	**6**
	SP	40	30	**6**
039	SP	20	30	**12**
	SP	40	30	**12**
040	SP	20	30	**48**
	SP	40	30	**48**
041	SP	20	30	**60**
	SP	40	30	**60**

Figure 3.17 - Deposit for ΔT=30°F (Test 15)

Figure 3.18 - Deposit for ΔT=45°F (Test 16)

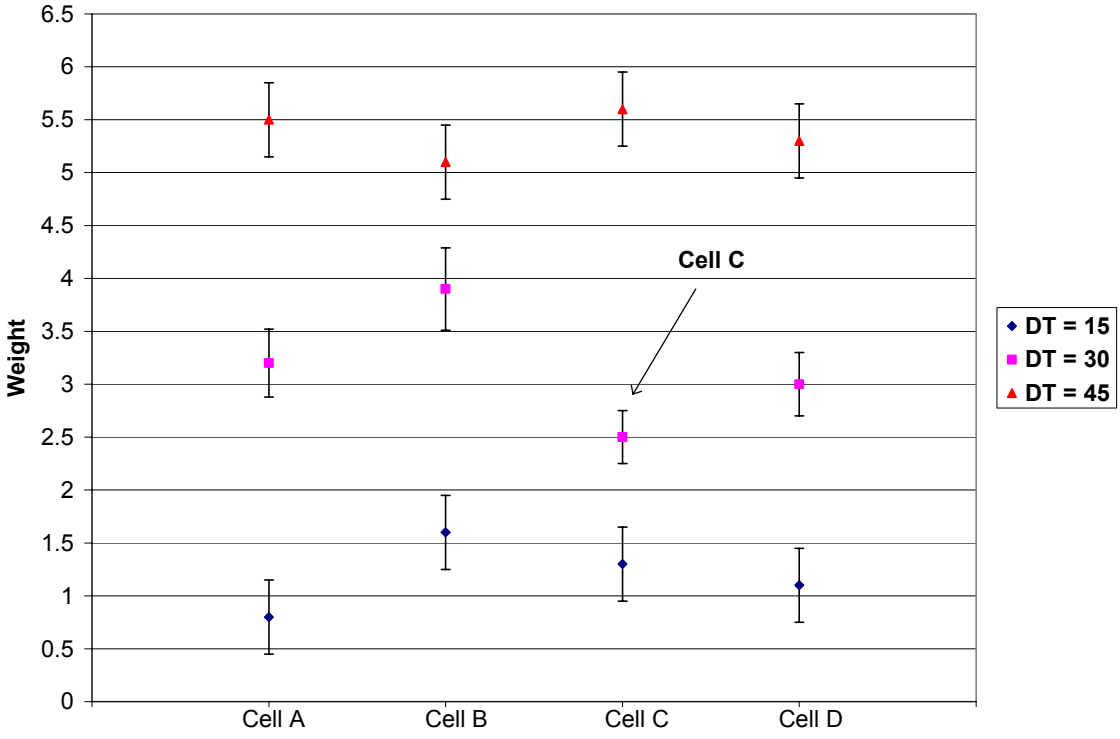


Figure 3.19 - Weight Profile as Function of ΔT for the Four Cells

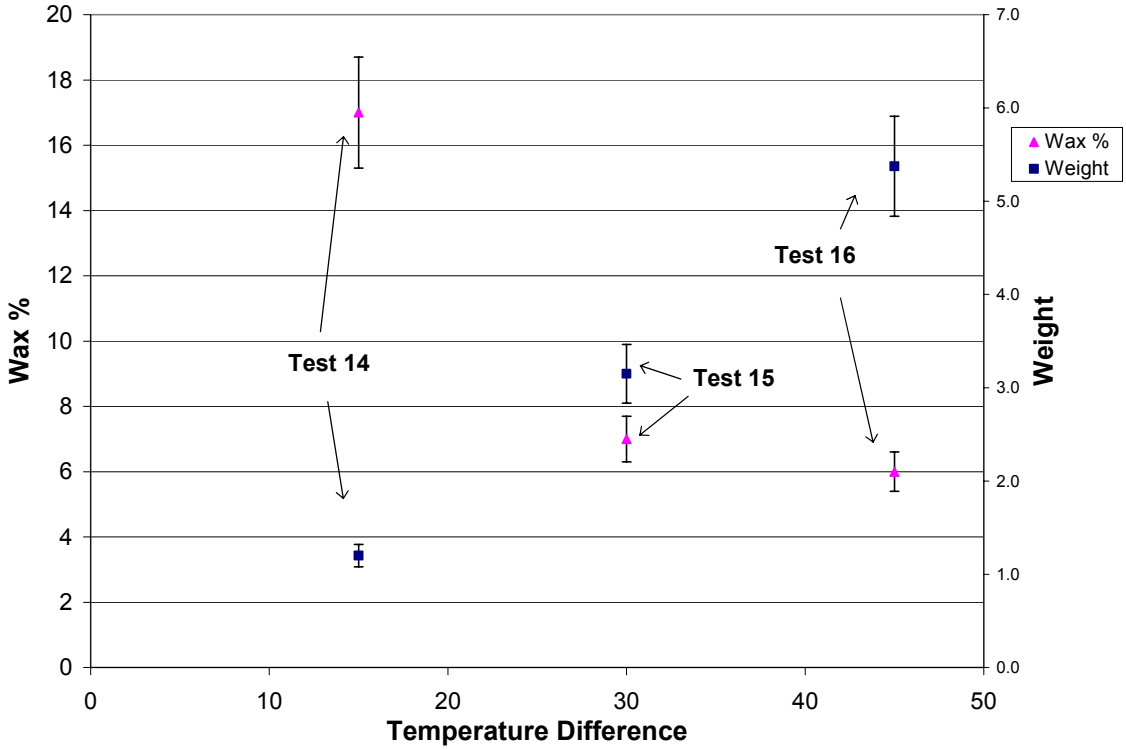


Figure 3.20 - Wax and Weight Profiles as Function of ΔT

Figure 3.21 – South Pelto and 20% Salt Water

Figure 3.22 - South Pelto and 40% Salt Water

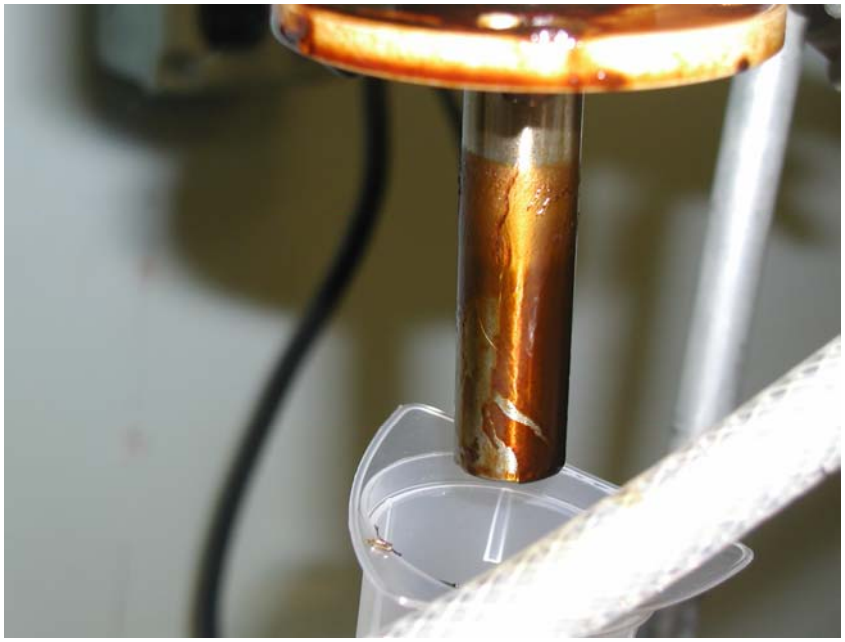


Figure 3.23 - 20% Water after Melting

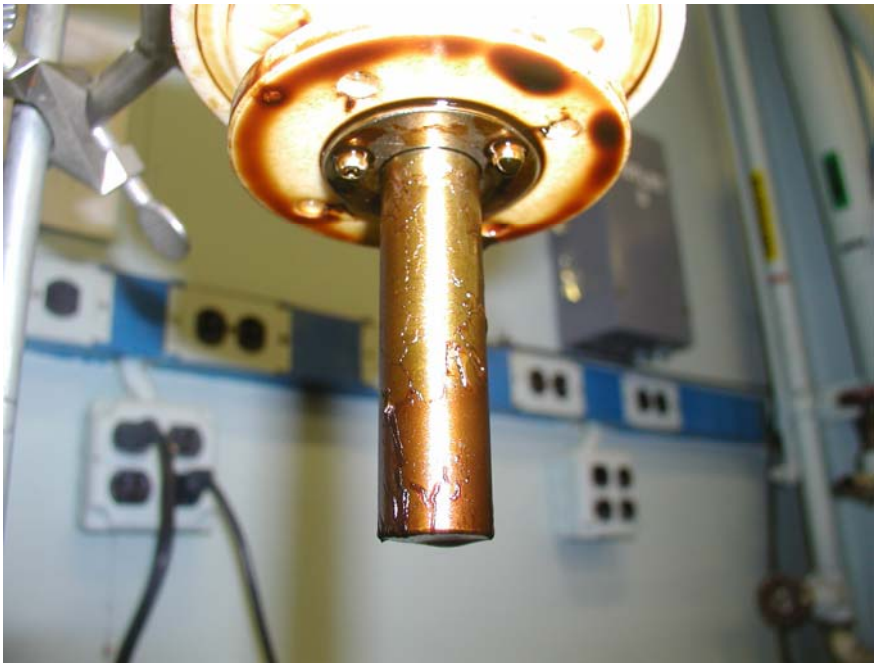


Figure 3.24 - 40% Water after Melting

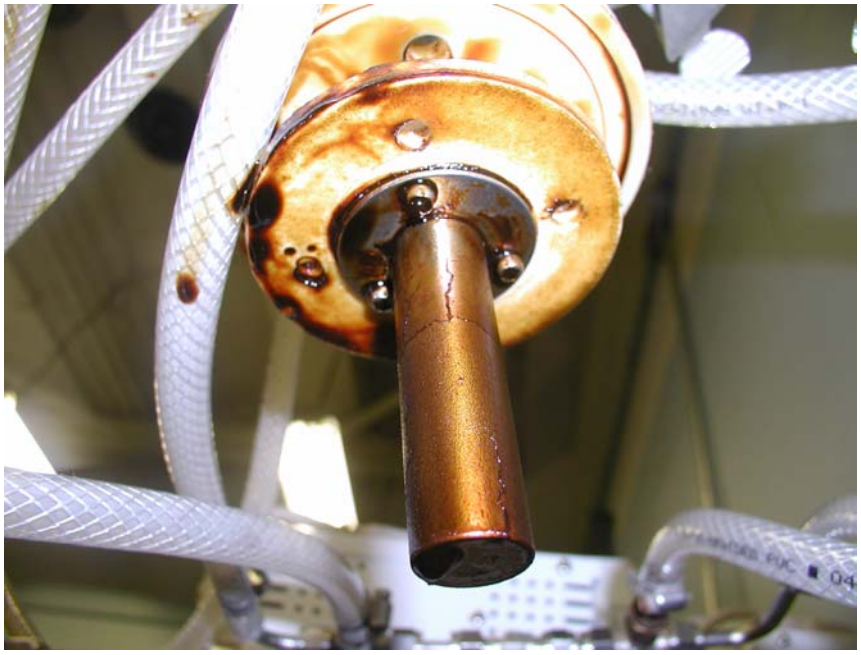


Figure 3.25 - 60% Water Cuts after Melting

Figure 3.26 - 80% Water Cuts after Melting

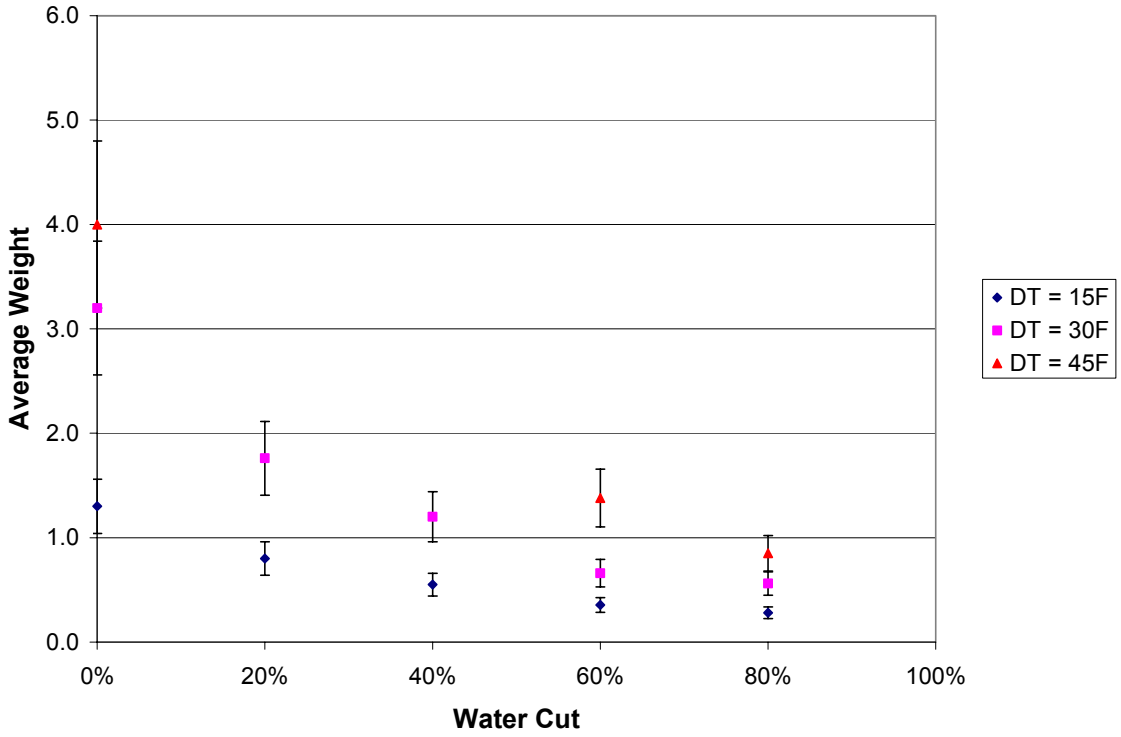


Figure 3.27 - Average Weight of Deposits as Function of Water Cut for Different ΔT

4. Modeling

a. Update of Wax Deposition Software

Since the last ABM, a few improvements have been made to the wax deposition software (TUWAX), including heat transfer calculations in the single-phase and multiphase wax deposition modules. The updated TUWAX is available now at the TUPDP website www.tufpc.org.

5. Conclusions

a. Small-Scale Studies

Tests in the three test sections with the same Reynolds number of 6300 have been completed. The oil and glycol inlet temperatures were 105ºF, and 75ºF, respectively for all tests. For the 1.5-in. diameter test section, deposit thickness reached 1.6 mm after 20 days. For the 1.0-in. diameter test section, deposit thickness reached 0.8 mm after 7 days. For the 0.5-in. diameter test section, deposit thickness reached 0.4 mm after 7 days. All of these above tests have been repeated and the results were reproducible. Unfortunately, depletion was confirmed and a bigger oil tank is needed.

Three oil-water two-phase tests were done to investigate the effect of water. All three tests showed faster wax buildup than the single-phase tests.

b. Single-Phase Studies

Better temperature control and easier interpretation of the data were accomplished for the tests by cooling outside the test section. With the new procedure, the effect of the temperature gradient was more evident at the beginning of the test.

The new data processing tool for thickness calculation based on pressure drop and outlet temperature changes provide better results when changes in the oil properties were considerable. With this new code, an interpretation of the cool-down period can be included for those tests where the cooling took place inside the test section.

The tendency of building thicker deposits as the temperature gradient increases could not be observed for CBI. The viscosity of the fluid is thought to play an important role since there are considerable changes that affect the diffusivity phenomena. The effect was not significant in fluids South Pelto oil and Garden Banks condensate.

Higher wax fractions inside the deposit were encountered at higher temperatures as well as harder deposits (not measured). The results were confirmed by higher differences between the LD-LD measurements before and after the MEK wash. One of the reasons is believed to be the lower viscosity that increases the mass diffusion.

The effect of the flow rate in the laminar regime was not as evident as in the turbulent flow. The same behavior was observed for tests with South Pelto oil. Similar to South Pelto oil and Garden Banks condensate, higher deposits were measured in spool piece 1 than in spool piece 2 for laminar flows.

Different thickness growth behavior was observed for CBI. For South Pelto oil and Garden Banks condensate, higher slopes were observed at initial times followed by a curve with nearly zero slope; possibly due to depletion problems, insulation, or shear effect. For CBI, a nearly constant and very low slope was observed for all tests. Differences between the thicknesses depended on very early time behavior due the temperature gradient effect on the oil.

Gel formation was observed in the spool pieces after shutdowns. A possible relationship between the amount of gel and the wall temperature was evidenced with less gel formation as the wall temperature increased. Enrichment of the “gel layer” due to the mass diffusion is speculated as one of the mechanisms for wax deposition for CBI. The presence of the gel was not observed with previous fluids possibly due to the lower viscosity values.

c. Two-Phase Studies

A total of 21 multi-phase tests were conducted in the multiphase flow loop using Garden Banks crude oil. Both horizontal and vertical flow test matrixes were completed. Also 8 repeat tests were conducted with new operating procedures.

- Garden Banks Horizontal flow tests:
  - ♦ Annular flow tests produced the thickest deposits.
  - ♦ Intermittent and stratified smooth produced thinner deposits of comparable values.
  - ♦ Stratified wavy produced thicker deposits than stratified smooth flow
- Garden Banks Vertical flow tests:
  - ♦ Bubbly flow and annular flow tests with high superficial oil velocities produced the thinnest deposits.
  - ♦ Intermittent flow tests with low superficial oil velocities produced the thickest deposit thickness.
  - ♦ Increase in oil superficial velocity results in thinner deposits.
- South Pelto deposition tests run under similar conditions produced thicker deposits, except for the intermittent vertical flow tests.
- The thickness calculations from heat transfer methods give good results compared to the results of online and offline LD-LD. The heat transfer method has an error band of +/- 0.11 mm with a confidence of 95%. If the value in the deposit thickness δ_w changes from 0.1 to 1 mm, its relative error changes from ±110% to ±11%.
- The thickness calculations from pressure drop measurements match with the measured thicknesses for the horizontal flow tests for South Pelto oil. Because there were fluctuations in the pressure data from the original Garden Banks horizontal flow tests, the pressure drop method did not yield any meaningful results. Also, if the thickness was too thin to yield significant change in the pressure drop, then pressure drop measurements can not be used. The thickness calculations from pressure drop measurements did not work for the vertical flow tests due to the predominance of the gravitational term in the total pressure measurement. The same problem was encountered with the South Pelto vertical test results. The predicted frictional pressure gradient compared to the total (or gravitational) pressure gradient was very small and the falling film friction overtakes the slug body friction.
- Most reliable methods for thickness calculations are from the online LD-LD and offline LD-LD. Online LD-LD has an error band of +/- 0.2 mm and the offline LD-LD gives results within +/- 0.025 mm with a 95% confidence interval for deposits around 1mm. However, if the thickness of the deposit changes from 1 to 0.1 mm, the relative error band increases from ±2.5% up to ±25%.
- Results of repeat tests produced very good agreements in overall thickness results from both online and offline LD-LD even though start-up method and ΔT were slightly changed. Therefore early deposition did not effect on the overall thickness results.

d. Three-Phase Studies

For single-phase tests, an increase in the temperature difference between the cold finger probes and the bulk oil results in an increase in the amount of deposits and a decrease in the deposit wax contents.

As the ΔT increases, the ratio between weight and wax content increases, resulting in much softer deposits. The higher oil contents associated with the heavier weight of the deposits can be seen by the sloughing of the deposits on tests at higher ΔTs.

For two-phase tests, the amount of deposits is less than single-phase tests. Four different water cuts have been tested with South Pelto crude oil at different ΔTs. An increase in the water cut results in a decrease in the amount of deposits for the same ΔT.

Four different ΔT tests have been run for two-phase conditions. A behavior similar to single-phase conditions has been identified. As the ΔT increases, the amount of deposit increases at the same water cut.

6. Future Work

a. Small Scale Studies

After completion of the depletion test, four single-phase comparison tests will be made to investigate the effect of velocity and shear stress. The test matrix is shown in Table 3.1. Tests with the same velocity and shear stress values in different test sections will also be conducted. Two sets of these tests are in the transition region and two are at a very low Reynolds number of 4000.

b. Single-Phase Studies

Transfer the fluid back into the tank and load the facility with Caratinga oil (Petrobras).

Start the fluid validation for the fourth fluid, including viscosity analysis, HTGC analysis. Design the test matrix based on the properties of the fluid and facility limitations.

Improve the current single-phase paraffin deposition model by including the thermal diffusion term.

c. Two-Phase Studies

South Pelto and Garden Banks will continue to be analyzed and compared, especially the wax content measurements from DSC results.

Two additional vertical tests will be run with Garden Banks Condensate to investigate the effect of the oil superficial velocity. The test conditions were given in Table 3.21.

d. Three-Phase Studies

After South Pelto tests results are completed, the CBI crude oil will be tested. Tests 23 to 25 will be run with the CBI crude oil to serve as single-phase tests baseline at a ΔT of 15, 30 and 45°F. Oil-water tests will be later run with 20%, 40%, 60% and 80% salt water contents over a period of 24 hours (tests 26 to 31).

The conditions for these tests will be:

Crude oil: CBI
Fluid Temperature: 85°F
Rotational Speed: 500 rpm
Period: 24 hours

After the completion of CBI tests, the aging tests are scheduled. Table 3.26 summarize the planned test matrix for these aging tests with South Pelto and CBI respectively.

Tests 32 to 36 will serve as a baseline with South Pelto single-phase oil tests, under conditions typical of the deposition facilities. A total of 10 aging tests are expected to be run with South Pelto. Tests 37 to 41 are two-phase tests, with 20%, 40%, 60% and 80% salt water contents.

Tests 42 to 45 will serve as a baseline with CBI single-phase oil tests, under conditions typical of the deposition facilities. A total of 10 aging tests are expected to be run with CBI. Tests 47 to 51 are two-phase tests, with 20%, 40%, 60% and 80% salt water contents.

This cold-finger test matrix might be further expanded or modified based on the available test results. The Garden Banks condensate is also available for testing.

7. Technology Transfer

a. Committees and Committee Meetings

The consortium has three working committees. The Model Validation committee deals with issues related to the operation and construction of the facilities as well as development of the test matrix. The Model Development Committee deals with issues related to developing and incorporating the algorithms and models developed into the code as well as the GUI requirements. They also provide input related to the test matrix. The Technology Transfer Committee deals with issues related to publications and the web site. The committee members and chair of each committee are given in Table 7.1.

Minutes from the Committee Meeting held during the April 2003 Advisory Board Meeting are in Appendix C.

b. Web Site

During the past few months, our web page has undergone a drastic transformation! We think you are going to like the new look and content and hope that you find the website more useful and easier to navigate.

From the front page of the website - you will be able to access both TUFFP and TUPDP websites. From this page you can access all the information regarding TUPDP, background information, publications, calendar, our facilities, and research projects and personnel. By the time you read this, all past TUFFP reports will be available to member companies on the website. There is also a valiant effort underway to resurrect all past programs written by students and place them on the web.

Member company names have now been linked to their respective websites. Links to TU Consortia will be provided along with links to other sites of interest. All users will have a unique login and password - if you haven't been notified of your login and password, please contact Linda Jones at jones@utulsa.edu or (918) 631-5110.

There have been two very significant additions to the web site. There is now a search engine available in the members' area, where you could look for research reports, programs, papers, etc., either by name, keywords, or author. Another addition will be mail lists that you can subscribe to. This will be a great place to come if you have inquiries and want input from other members. The new url is www.tufpc.org. Please let us know how we can further improve the Web site.

c. Future Meetings

The Spring 2004 Advisory Board Meeting will be held on Thursday, April 1st. The location of the meeting has not yet been determined.

Table 7.1 – Committee Organization

Committee	Model Development	Model Validation	Technology Transfer
Industry Chair	Probjot Singh ConocoPhillips	Jeff Creek ChevronTexaco	Steve Allenson ONDEO Nalco Energy Services
TU Representatives	James P. Brill	Cem Sarica	Michael Volk
	Holden Zhang	Emmanuel Delle Case	Linda Jones
Members	Klaus Weispfennig Baker Petrolite	Chris Gallagher Baker Petrolite	John Roscoe Marathon Oil Company
	Katherine Scurrah BG Technology	David Jennings Baker Petrolite	Sharon Buffington Minerals Management Service
	Scott Hickman ExxonMobil	Ann Davis Champion Technologies	Elijah Kempton Multiphase Solutions, Inc.
	Nagi Nagarajan ExxonMobil	Tom Williams Champion Technologies	Jose Manuel Reyes Aguirre Pemex
	Federico Gonzalez Tames Pemex	Bill Thomason Conoco, Inc.	David Zornes Phillips Petroleum
	George Broze Shell E & P Technology	Scott Hickman ExxonMobil	Mathew Zielinski Unocal Corporation
	Jack Hsu ChevronTexaco	Nagi Nagarajan ExxonMobil	
		Todd Bullerdick Marathon	
		Miguel Araya ONDEO Nalco Energy Services	
		Norman Byrne ONDEO Nalco Energy Services	
		Federico Gonzalez Tames Pemex	
		Samir Gharfeh Phillips Petroleum	
		Claude Schranz TotalFinaElf	

8. Administrative Issues

a. Task Schedule Status

Modified task schedules for the three projects are shown in Figs. 84 - 86. The charts are color-coded. Black is the schedule as proposed. If the activity is color coded blue  , the task is now complete. A task colored in red  was either rescheduled or added.

Before any single-phase tests were conducted with the CBI crude oil, tests using three fluids with different viscosities were run to get a better understanding on how to process the pressure data. Upon completion of these studies the flow loop was cleaned and charged with the CBI crude oil. The single-phase tests with CBI crude oil have been completed. The facility will be cleaned and testing with the Caratinga crude oil will begin.

Multiphase testing with the Garden Banks condensate continued. These tests were repeat tests with the new startup procedure; The next set of tests conducted in the multiphase loop will be the gas-oil-water tests using the Garden Banks condensate and a salt saturated brine.

The small scale test matrix was discussed at the April 2003 ABM with the technical committee and then reviewed with the participants. As a result of the input received, the test matrix was modified as follows.

1. Run water-oil tests with the South Pelto black oil using water cuts of 25 and 50% to gain insight as to the impact of water on the deposition process prior to running gas-oil-water tests,
2. Conduct tests to quantify the respective shear stripping, insulation and depletion effects on our flow loop tests - two long term tests with changes in ΔT during the experiment, as well as changes in the initial oil charge, backed up by specific DSC analyses would be conducted to provide answers on the relative importance of insulation, shear stripping and depletion effects in flow loop tests. This could have a significant impact on system design should the wax growth in turbulent flow turn out to be limited by the shear stripping effects,
3. Run tests with the South Pelto black oil using the 0.5, 1.0 and 1.5 inch flow loops at constant velocity and constant shear to better understand how to scale-up the results,
4. Run tests with the Garden Banks condensate using the 0.5, 1.0 and 1.5 inch flow loops at the best scaling parameter determined in step 2 above,
5. Run a long term test (27 days) with the Garden Banks condensate to understand the effects of shear stripping and aging,
6. Run water-oil tests with the Garden Banks condensate using water cuts of 25 and 50% to gain insight as to the impact of water on the deposition process,
7. Run tests with a heavy oil, Cote Blanch Island, using the 0.5, 1.0 and 1.5 inch flow loops at constant Reynolds Number, velocity and constant shear to better understand how to scale-up the results, and
8. Run a long term test (27 days) with the Cote Blanch Island heavy oil to understand the effects of shear stripping and aging.

Testing with S. Pelto will be completed shortly after the Advisory Board Meeting. The loop will be cleaned and testing with Garden Banks will begin. Testing with Caratinga will begin in February. These results will be used in our efforts to scale up field data.

b. Membership

Currently there are twenty member companies of the consortium. These member companies include: Baker Petrolite, BG International, BHP Billiton Petroleum, BP, Champion Technologies, ChevronTexaco Exploration and Production Technology Company, Conoco-Phillips, Department of Energy (DOE), ExxonMobil Upstream Research, Japan National Oil Corporation, Marathon Oil Company, Minerals Management Services, Nalco Energy Services, ONGC, Pemex, Petrobras, Shell E & P Technology

Company, Statoil, Total and Unocal. Three companies participate as "in-kind" members: Alberta Research Council, Multiphase Solutions, Inc. and PetroCanada.

c. Continuation Proposal

At the last Advisory Board Meeting for the Tulsa University Paraffin Deposition Projects, we discussed twelve research topics for continuation of the current study. Questionnaires were passed out for completion by the member companies. These survey results were to be used to develop the work plan for the continuation efforts of the Consortium.

We received completed questionnaires from most of the member companies. The research topics are listed in order of priority, i.e. from high to low. At this time, we will focus on the first eight research topics in the continuation work statement. In summary, the topics of interest can be grouped as follows:

1. Shear and Aging Studies
2. Model Development and Validation Studies
    a. Gel Layer
    b. Rigorous Heat Transfer for Slug Flow
    c. Oil-Water
    d. Gas-Oil-Water
3. Pigging Efficiency Studies

A brief write-up of the tasks was prepared for review and input was requested from the committee chairs. Additional input will be received when the proposal is presented and discussed during this Advisory Board Meeting.

Figure 8.1 – Single-Phase Studies

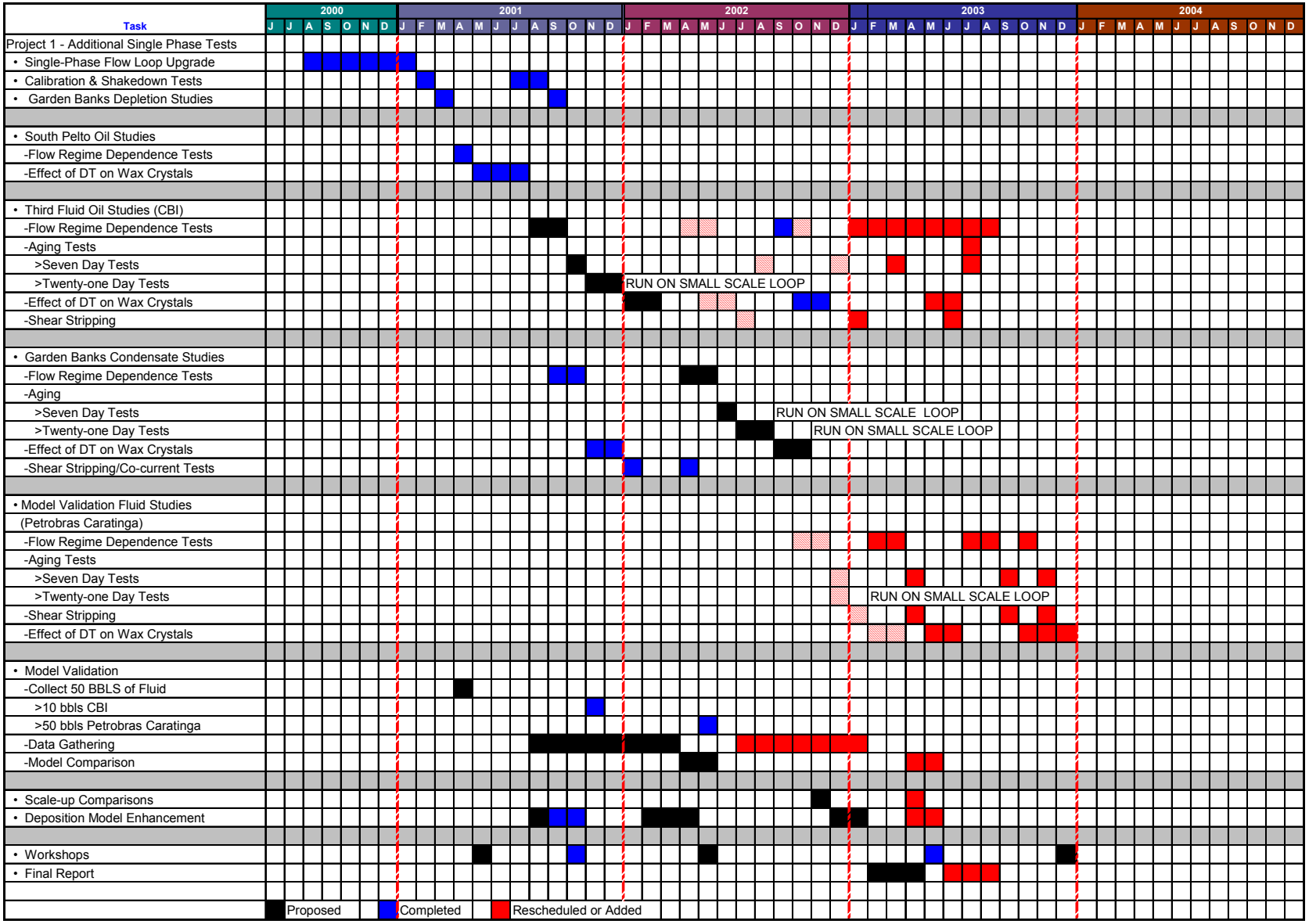


Figure 8.2 – Multiphase Testing (Gas-Oil and Gas-Oil-Water)

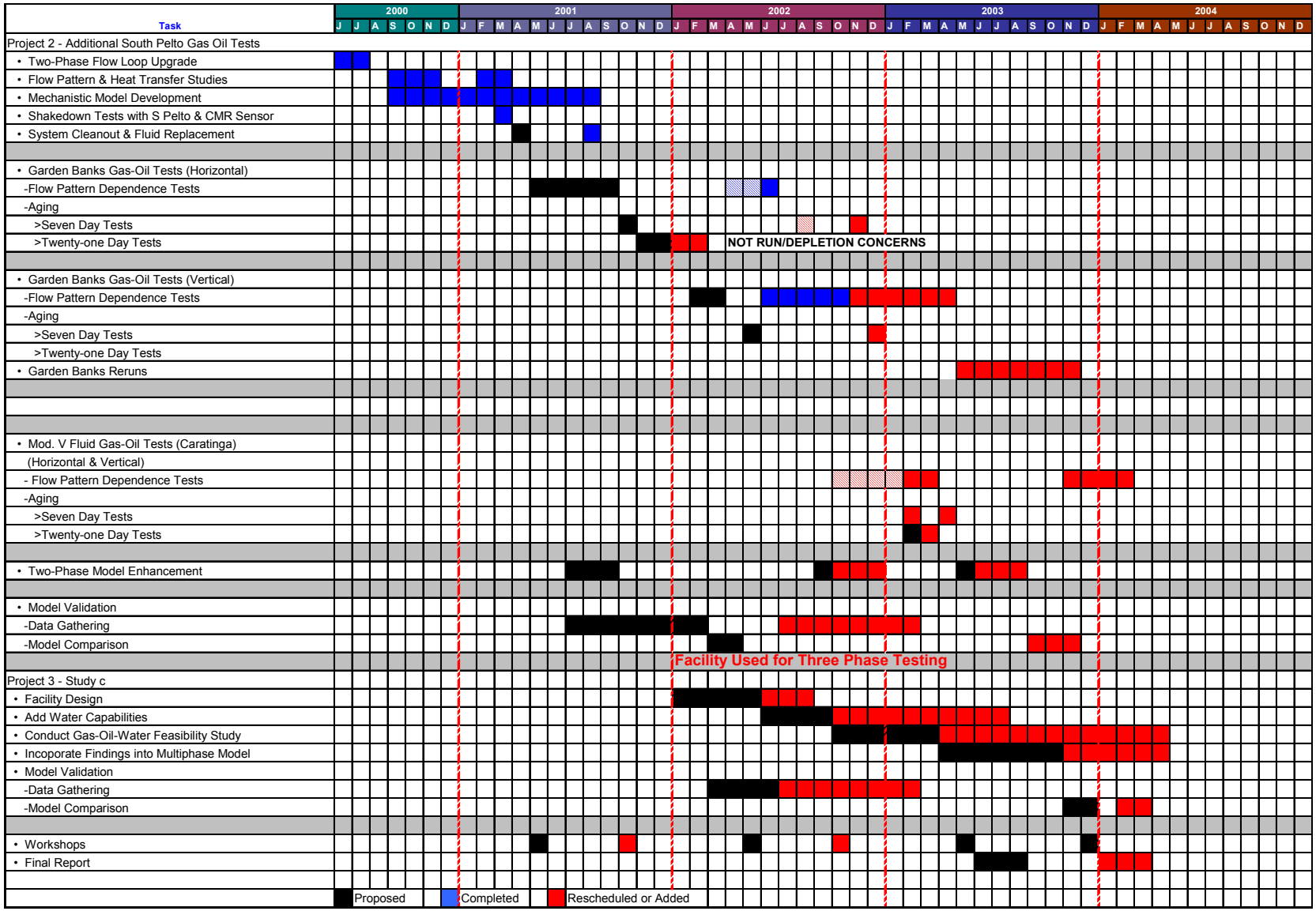
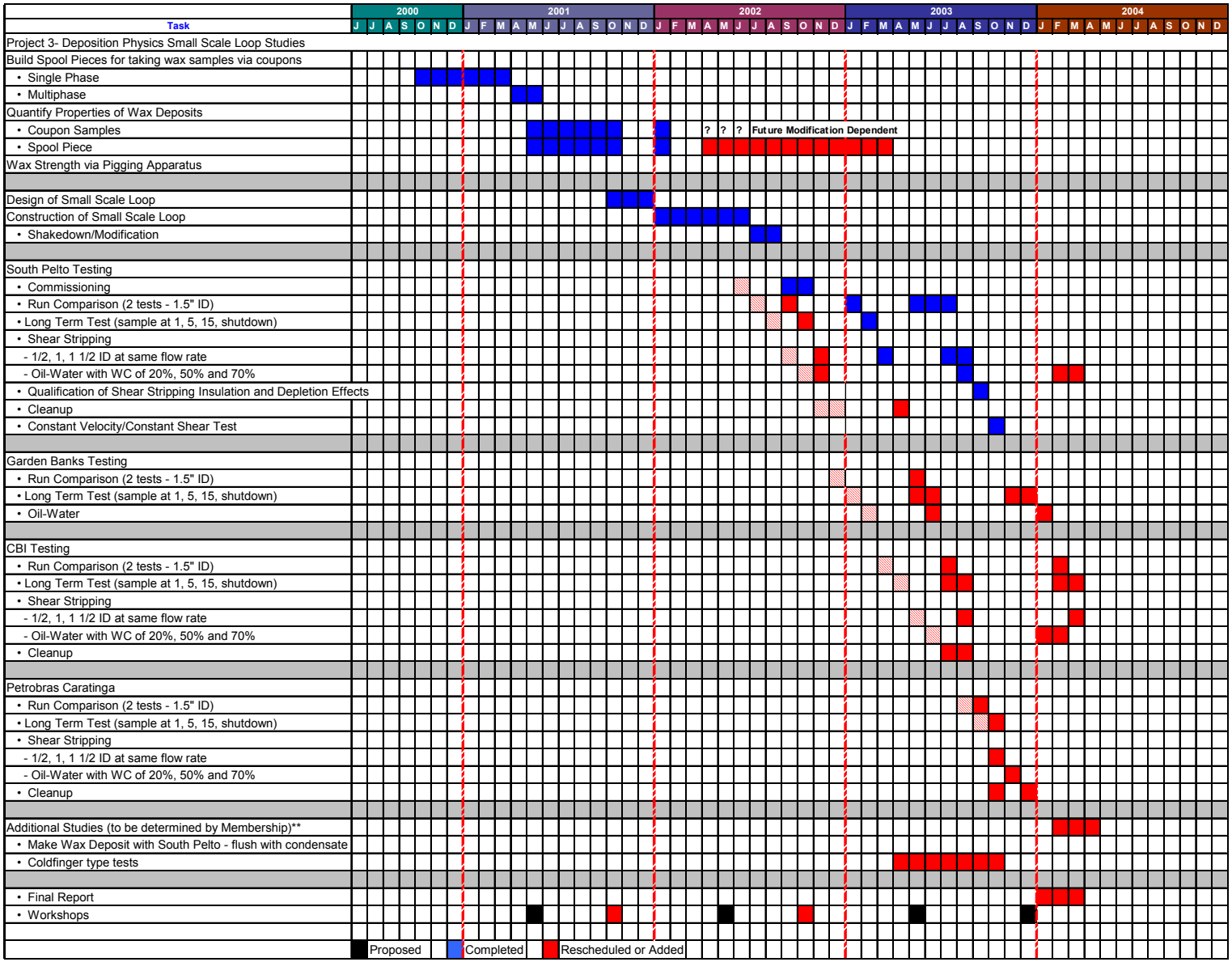


Figure 8.3 – Deposition Physics Small Scale Loop and Water Impact Studies



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10. List of Acronyms and Abbreviations

BPD – Barrels Per Day

CBI – Cote Blanche Island

CMR – Christian Michelsen Research

CNG – Compressed Natural Gas

CPM – Cross-Polar Microscopy

CPVC – Chlorinated Polyvinyl Chloride

DAQ – data acquisition

DCS – Distributed Control System

DOE – Department of Energy

DOT – Department of Transportation

DP – Differential Pressure

DSC – Differential Scanning Calorimeter

FPSO – Floating Production Storage and Offloading

HTGC – High Temperature Gas Chromatograph

ID – internal diameter

JIP – Joint Industry Project

LD-LD – Liquid Displacement – Level Detection

MEK – Methyl Ethyl Ketone

MSI – Multiphase Solutions, Inc.

OSU – Oklahoma State University

PC – Personal Computer

PID – Proportional, Integral and Derivative

PT – Pressure Transducers

PVC – Polyvinyl Chloride

RTD – Resistance Thermal Detectors

SCADA – Supervisory, Control, Alarm and Data Acquisition

TLP – Tension Leg Platforms

TU – Tulsa University

TUFFP – Tulsa University Fluid Flow Projects

TUPDP – Tulsa University Paraffin Deposition Projects

WAT – Wax Appearance Temperature

Appendix A – Table of Deliverables

1. Tulsa University Paraffin Deposition Prediction Research and Model Validation Consortium – Kickoff Meeting Activities – May 23, 2000.
2. Operating Committee Meeting Minutes – August 4, 2000
3. "TUFFP and TUPDP Programming Guidelines and Nomenclature Standards" – September, 2000
4. Model Development Committee Meeting Minutes – October 4, 2000
5. Tulsa University Paraffin Deposition Projects (TUPDP) Advisory Board Meeting Brochure and Slide Copy – November 15, 2000.
6. Model Validation Committee Meeting Minutes – November 15, 2000
7. Model Development Committee Meeting Minutes – November 15, 2000
8. "Multiphase Flow Wax Deposition Modeling" paper and presentation presented at the ETCE 2001 – February 5-7, 2001.
9. "Evaluation of the Waxing Potential for South Pelto" results of testing by MSI – April 5, 2001
10. Multiphase Wax Program and Updater – May, 2001
11. Tulsa University Paraffin Deposition Projects (TUPDP) Advisory Board Meeting Brochure and Slide Copy – May 23, 2001.
12. Model Validation Committee Minutes – May 23, 2001
13. Model Development Committee Minutes – May 23, 2001
14. Tulsa University Paraffin Deposition Projects (TUPDP) Advisory Board Meeting Brochure and Slide Copy – October 4, 2001.
15. TUPDP Modeling Workshop, New Orleans, Louisiana – October 5, 2002
16. Evaluation of the Waxing Potential for Garden Banks, Results of Testing by Multiphase Solutions, Inc. – October 1, 2001
17. Model Development Committee Meeting Minutes – October 4, 2001
18. Model Validation Committee Meeting Minutes – October 4, 2001
19. Technology Transfer Committee Meeting Minutes – October 4, 2001
20. HTGC Wax Analysis Results for South Pelto Tests, Results of Testing by ChevronTexaco Exploration and Production Technology Company – September 2001.
21. Multiphase Wax Program, Version 4.03 – March 2002
22. Tulsa University Paraffin Deposition Projects (TUPDP) Advisory Board Meeting Brochure and Slide Copy – April 24, 2002

23. Model Development Committee Meeting Minutes – May 24, 2002

24. Model Validation Committee Meeting Minutes – May 24, 2002

25. Technology Transfer Committee Meeting Minutes – May 24, 2002

26. Hernandez, O., "Investigation of Single-Phase Paraffin Deposition Characteristics," M.S. Thesis, U. of Tulsa (2002).

27. Tulsa University Paraffin Deposition Projects (TUPDP) Advisory Board Meeting Brochure and Slide Copy – October 9, 2002

28. Technology Transfer Committee Meeting Minutes – October 9, 2002

29. Model Development Committee Meeting Minutes – October 9, 2002

30. Model Validation Committee Meeting Minutes – October 9, 2002

31. TUWAX v. 2003.01, January, 2003

32. Tulsa University Paraffin Deposition Projects (TUPDP) Advisory Board Meeting Brochure and Slide Copy, April 16, 2003.

Appendix B – Minutes of the Model Development Committee Meeting – April 16, 2003

Attendees: All participants of the Advisory Board Meeting.

The discussion was started with the heat-mass transfer analogy (such as Chilton-Colburn analogy) used in modeling wax deposition under turbulent flow. Some participants suggested that the heat-mass transfer analogy should be applicable for the turbulent flow and are valid for a range of Schmitt and Prandtl numbers. Heat and mass transfer analogies are based on an assumption that the mass transfer is independent of heat transfer. Because of the fact that the mass transfer for the case of wax deposition strongly depends on the heat transfer, the differential equations for the heat and mass transfer are coupled and hence the analogy currently being used in the film model may not be valid. The discussion was leading towards solving coupled heat and mass transfer equations for the viscous boundary layer in the turbulent flow and developing a heat and mass transfer analogy from the first principle, which is applicable for the wax deposition.

The current mathematical model assumes wax as one lumped component that goes through a phase change during the wax deposition process. Wax in crude oil is a multi-component system composed of different n-alkane molecules with a range of carbon numbers. The solubility and diffusivity of n-alkane in a crude oil are functions of the size (carbon number) of the n-alkane molecule. The current model assumes one lumped solubility and diffusivity of wax components in the crude oil. The discussion went in the favor of developing multi-component wax deposition model and comparing the results with the current model. The multi-component model would also answer whether some heavier wax components (say carbon number > 40) are getting depleted in our flow loop experiments.

Various other complex facets of the physics of wax deposition were briefly discussed such as shear effects, kinetic effects and possibility of moving gel deposit. To capture these different mechanisms in the flow loop experiments as well as in the mathematical model is a real challenge ahead of us.