LABORATORY PROGRAM DESIGN FOR UNCONSOLIDATED HEAVY OIL RESERVOIRS: A CASE STUDY

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ABSTRACT

Laboratory programs for unconsolidated heavy oil reservoirs encompass basic core analysis, grain size analysis, geological and petrological studies, and supplementary core analysis tests such as relative permeability, resistivity, fines migration, and clay swelling. The results from a recent program illustrate that effective program design is required in order to obtain the best quality data, and to achieve the maximum economic benefit.

Geological, petrophysical, and reservoir simulation studies on an unconsolidated, conglomeratic sandstone required input of laboratory data including porosity, permeability, fluid saturations, formation factor and resistivity index, and relative permeability. Petrological studies were utilized to supplement geological interpretation. Based upon available information about the reservoir, these tests were sequenced in the order in which the results were required for the subsequent engineering and geological studies. As a result, relative permeability was one of the first tests performed, and anomalous data were obtained. Integration of grain size and petrological data with the relative permeability data, and with the results of a fines mobilization test, resulted in the anomalous data being interpreted and explained. This integrative approach to laboratory data interpretation pointed out the need to modify further experiments in order to achieve meaningful results.

Based on this experience, a sequence of laboratory testing is recommended for suites of samples from unconsolidated heavy oil reservoirs. This sequence allows identification of reservoir problems, such as mobile fines, before they can impact complex laboratory experiments such as relative permeability. Therefore, this test sequence maximizes the potential for obtaining high quality data from all the laboratory tests, particularly the more expensive and time consuming ones.

INTRODUCTION

A complete suite of analyses were undertaken on samples from 2 wells in an unconsolidated heavy oil reservoir. The analyses, summarized in Table 1, included basic core analyses, petrological studies, and supplementary core analyses. The laboratory study was part of a multi-company joint venture integrating petrophysical analysis, geological mapping, and reservoir engineering and simulation in a comprehensive reservoir evaluation.

The data derived from the laboratory tests were to be utilized in the other studies and consequently, there was a limited time frame for providing that data within the total scope of the project. Therefore, it was not possible to do the laboratory tests in a sequential order, but rather, most had to be carried out simultaneously (Figure 1). This order of the analyses did not permit the results from one test, or series of tests, to be utilized in the design of further testing. It should be noted however, that at the time the project was designed, the available geological and engineering data did not indicate that problems would be encountered by using this approach.

This paper discusses the results of the laboratory program, and the changes and additions that had to be made, due to an ongoing evaluation of the results. Based on the experiences gained in this project, recommendations are made with respect to future laboratory programs in similar reservoirs.

SAMPLE ACQUISITION AND PREPARATION

Because of the client's requirements, the complete cores from the 2 wells could not be taken to the laboratory complete. Rather, the samples had to be obtained in the field. Facilities were therefore established to enable obtaining a core gamma, core photographs, a geological description, and the actual samples at the well site.

Samples from each well were selected based on the core gamma log and the geological description, as well as the client's geological knowledge of the reservoir. Enough samples had to be selected to ensure that all planned analyses could be completed.

The samples were drilled with a plug core bit, using liquid nitrogen as a lubricant. The plugs were sleeved with teflon and the ends were capped with screens. After sleeving, the samples were placed in an insulated box with dry ice for shipment to the laboratory. A few full diameter samples for thermal properties testing were also wrapped and frozen.

BASIC CORE ANALYSIS

Basic core analysis consisted of mass fraction analysis of oil, water, and solids using the Dean Stark method, plus porosity, permeability and grain density determinations. In addition, grain size analysis was done on selected samples using the dry sieve method.

Fluid saturation data appeared to be of good consistent quality, and was used confidently in the subsequent petrophysical analysis, although some anomalous values were noted in a water leg which had suffered mud invasion. The porosity and permeability data were also of good quality, although many of the values were high ($\phi \geq 35\%$; $k > 5$ darcies). These results had been expected. In a number of cases, where companion vertical plugs had been taken adjacent to horizontal plugs, the permeability results obtained indicated a higher vertical permeability than horizontal permeability. More detailed examination of each of these samples indicated two possible sources of error which would result in the high vertical permeabilities:

- The samples were taken from very short cored intervals, indicating areas of poor core recovery and therefore, strong disturbance.
- The samples were taken from pebbly or conglomeratic zones due to the limitations of the sampling process in the field. Where large pebbles were present, they created a permeability path along their edges, resulting in unrealistically high permeability values. The presence of large pebbles in plug samples resulted in permeabilities that were not representative of the reservoir. The influence of the pebbles tended to be dominant in the plugs, whereas they had little influence in the sands of the reservoir.

Dry sieve analysis utilizing 8 screens, was performed on selected samples. The results showed the samples to be moderately to poorly sorted, with 70% having a significant (>7%) fines (≤ .044 mm) component. The finer portion of the samples, the -325 sieve fraction (≤ .044 mm), was not analyzed.

PETROGRAPHICAL ANALYSIS

While the basic core analysis was ongoing, preliminary petrographic examination was carried out on 60 pre-chosen samples, of which 30 were selected for detailed petrographic analysis, supplemented by selected scanning electron microscopy and bulk and glycolated clay x-ray diffraction analysis. Samples were chosen to represent a range in lithologies, matrix content and mineralogic variations within each of the reservoir beds. In addition, 6 samples were selected for steam testing and related scanning electron microscopy to assess the potential for mineral transformations (1) that could occur under the elevated pressures and temperatures of an EOR recovery project.

The sand samples were found to be moderately to well sorted with mean grain size varying from mid-upper very fine grained sand to lower mid coarse grained sand. The conglomeratic samples were bimodally sorted: the fine grain size population generally ranging from silt size or very fine grained sand to medium to very coarse grained sand; very coarse grained sand to pebble size clasts comprising the coarse population. Matrix clays were present in trace to abundant amounts. In general, these matrix clays were a mixture of smectite, mixed-layer clays, kaolinite and illite, with chlorite content varying from absent to minor amounts.

On the basis of the petrology data, sand production and migration were predicted to be the most significant reservoir quality problem. Samples containing abundant matrix clays were interpreted to be sensitive to fresh water in terms of clay swelling. Potential mineral transformations including dissolution and reprecipitation of silica and formation of smectite were identified as possibly occurring at the elevated temperatures of a steam flood. Based on the data, it was interpreted that the passage of a steam front could result in the migration of a mixture of hydrocarbons, clays and fines, resulting in an increase in fines migration or sand production problems as well as a decrease in permeability.

Six samples were subjected to static steam treatment. These samples were selected on the basis of the petrological analysis previously described. At the conclusion of the steam treatment, portions of each sample were examined utilizing a scanning electron microscope. No mineralogical changes were observed, although the possibility had been predicted as a result of the petrological analysis.

SUPPLEMENTARY CORE ANALYSIS

A number of supplementary core analysis tests were undertaken as part of this study (Table 1). Only those which were affected by the sequence of the tests are described below. These tests include electrical resistivity, relative permeability, and clay swelling/fines mobilization.

Electrical Resistivity Tests

A reservoir electrical resistivity study was carried out on 16 samples. The formation resistivity factors for the two wells were consistent, while the hydrocarbon resistivity indexes among the samples varied, with saturation exponents ranging from 1.61 to 4.30 with the composite index being 1.88 for one well and 2.48 for the other. There was no explanation, based on the lab data alone, for the discrepancy in the composite values.

Subsequent discussions with the client indicated that the variations between the wells could be explained if the results of the analysis were separated according to individual beds, although until that time, all beds within the field had been treated as a single reservoir. Based on this information, it was concluded that the composite hydrocarbon resistivity index should have been generated only on a bed by bed basis due to the variations between each bed.

Relative Permeability Tests

Two suites of unsteady state relative permeability tests were performed. The first test was initiated prior to completion of the routine analysis and the petrographical evaluation of thin sections. Consequently, visual examination of the core samples was relied upon, and high permeabilities were anticipated. The objective of the testing was to determine relative permeability curves at each of 100°C, 175°C and 250°C on the same stack of samples. In anticipation of the high permeabilities, the stack was composed of four plugs, and was capped with two screens at either end, 120 mesh and 325 mesh. As testing of the sample proceeded, extremely high differential pressures were encountered, resulting in deformation of the sample. In addition to the high pressures, poor oil production was observed. As the experiment progressed, it was evident that fines were being produced, since particles could be observed in the sight glass used to collect the core effluent, and these fines affected the oil readings taken in the sight glass. Upon completion of the testing, it was found that permeability had been significantly reduced, and there was a high residual oil saturation.

Due to the problems encountered in testing of the first sample, a portion of it was examined by scanning electron microscopy. Significant fines migration had occurred, plugging the screens and resulting in packing of the fines against the screens. This caused the permeability loss. Based on this information, it was interpreted that the high viscosity (1300 cp) of the oil at 100°C had resulted in the massive fines mobilization problem. Relative permeability curves could be generated (2) for the data based upon the endpoint oil permeability, but the results were poor and difficulty was encountered in obtaining history matches, and hence in obtaining good curves. Consequently, it was concluded that the results from this suite of testing might not be representative of reservoir conditions.

Based on the evaluation of the above relative permeability test, and with the availability of the results of the petrological study, it was evident that fines migration was posing a significant problem in the testing of these samples. It was therefore decided to utilize higher temperatures during testing to try and reduce the viscosity of the oil and also the differential pressures. It was also decided to use smaller stacks of two plugs each; the first stack was tested at two temperatures, 150°C and 200°C, and the second stack was tested at 250°C only.

Differential pressures during the second series of tests were lower than those encountered during the first testing and oil recovery was much improved. Examination of the sample subsequent to the test revealed that significant fines migration had again occurred and, even though a larger screen size (120 mesh) was utilized on the production end, there was still plugging of the screen and a related reduction in permeability. However, interpretation of this data to generate the relative permeability curves resulted in good history matches and these curves were judged as being a reasonable representation of relative permeability within the reservoir.

Due to the difficulties encountered with the relative permeability testing, modified steam recovery tests were performed in order to obtain residual oil saturation values after steamflood for use in reservoir simulation studies.

Clay Swelling/Mobilization

The chemical sensitivity and mechanical stability of the water rock system comprising the reservoir were studied using dynamic clay swelling and fines mobilization tests (3) on one sample from each well.

No significant decrease in permeability was observed when formation brine and tap water were injected into the samples. The petrological study indicated that smectite, which will expand when exposed to fresh water, is variable in its distribution throughout the reservoirs.

Based on the smectite content in some samples (determined by x-ray diffraction analysis) significant clay swelling was expected in the intervals represented by those samples. Other intervals, however, had only trace to minor amounts of smectite and were not anticipated to develop clay swelling problems which would result in reduced permeability. Unfortunately, x-ray diffraction analysis and detailed petrological studies were not performed on the samples which were subjected to the clay swelling and fines mobilization tests. Based on the test data it was concluded that the intervals, as represented by the tested samples, were not susceptible to clay swelling, and therefore probably did not contain significant amounts of smectite.

The fines migration tests indicated significant problems with respect to fines mobilization. Fines were collected during saturation of the sample, and during actual testing. Fines appear to have been dislodged during the saturation process due to application of a small pressure gradient used to ensure total saturation. From the test results, it therefore appeared that the application of any pressure gradient on these samples was sufficient to mobilize fines. Consequently, the liquid permeability had been reduced before any dynamic displacement experiments were performed.

The first fines mobilization test was performed using a 120 mesh end screen. At completion of the test, it was observed that there was significant blockage of the screens and that this blockage had resulted in fines backing up behind the screen, causing a severe permeability loss. As a result, the second test was modified: a 24 mesh screen was utilized on the ends of the sample, and a lower differential pressure was used during saturation. Testing of the second sample resulted in a much less significant decrease in the permeability. The fines were permitted to flow through the screen, with less blockage of the screen and hence much less reduction in permeability. The fines were captured on a downstream filter.

These tests therefore confirmed the potential for fines migration observed during the petrological study. They also explained why significant problems were encountered during the relative permeability tests.

CONCLUSIONS

The results obtained during the various lab tests complemented each other and led to consistent interpretations of the data. In retrospect, it would have been preferable to perform certain test in advance of other tests, so that problems such as those that were incurred with the relative permeability tests could have been anticipated. Therefore, based on this experience, it is recommended that future laboratory testing for similar reservoirs should be designed to incorporate the following:

1. The entire core should be frozen in the field and should be removed to the laboratory so that it can be sampled and analyzed systematically and sequentially.

2. All basic core analysis should be completed prior to selection of samples for petrological and supplementary core testing. This will enable maximum utilization of porosity and permeability data in the selection of appropriate samples which would be representative of the various beds in the reservoir.

3. After completion of the routine core analysis, and prior to initiation of any of the supplementary core analysis, a petrological study of the well(s) to be studied should be undertaken in order to determine (in conjunction with the detailed core description), the facies that are present, the mineralogy, and any reservoir quality problems, such as fines migration, which may be anticipated.

4. Samples should be selected for supplementary core analysis utilizing the results of the basic core and petrological analyses. These samples should be screened, to determine if they are homogeneous, using non-destructive x-ray methods.

5. Electrical resistivity measurements should be carried out to determine the formation factors hydrocarbon resistivity index values which should be utilized in log interpretation for the reservoir. Data from different beds should be analyzed separately rather than as a single reservoir.

6. Dynamic testing can be initiated at the same time as the electrical resistivity studies, but the first tests which should be undertaken is fines mobilization/clay swelling. Undertaking these tests prior to other tests will identify potential problems due to injection of fresh water, and the severity of the problem of fines migration. Potential problems with laboratory procedures can then be anticipated and appropriate changes can be made.

7. After obtaining results of the fines migration tests, samples should be selected for steam recovery tests. These tests should be run prior to the running of the relative permeability tests, because values for residual oil saturations will be obtained, and these can be used as comparisons during evaluation of the relative permeability tests.

8. Relative permeability tests should be the last of the displacement tests run. Based on the results of the current study, it is recommended that samples of similar lithology not be stacked, but rather that individual plugs be utilized. Each plug should be used for a single test only so that if fines mobilization does occur, it will only affect one set of data.

The proposed sequence of laboratory tests summarized in Figure 2, would no doubt require a longer time frame than that which was utilized during the current study, probably an additional 2 months (a 40% increase). However, if laboratory data is to be properly assessed and evaluated and is to be used properly in reservoir evaluation and modelling studies, it is imperative that the tests be carried out in the proper order. If problems can be anticipated, proper design of experiments can be made in order to obtain the best quality data in an economic manner.

REFERENCES

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TABLE 1: SUMMARY OF CORE TESTS

Type of Analysis	Data Usage
1. Basic Core Analysis	
Mass Fraction Oil/Water/Solids	Petrophysics/Simulation
Porosity/Grain Density/Permeability	Petrophysics/Simulation
Grain Size Analysis	Geology/Production
2. Petrology	
Detailed Thin Section Analysis	Geology
XRD and SEM Studies	Geology
Steamflood Analysis	Geology/Production
3. Supplementary Core Analysis	
Electrical Properties	Petrophysics
Steam Recovery	Simulation
Clay Swelling/Fines Mobilization*	Production
Capillary Pressure (Imbibition)*	Client - not used in study
Relative Permeability	Simulation
Pore Volume Compressibility	Simulation
Rheology	Client - not used in study
Thermal Properties	Client - not used in study
*not in original program	

FIGURE 1: SCHEDULE OF LABORATORY PROGRAM

	MONTH 1	MONTH 2	MONTH 3	MONTH 4	MONTH 5
Basic Core					
Plug Cleaning	------------------------				
Fluid Saturations	-----				
Porosity/Permeability	-----------	-----			
Sieve Analysis	-----	-----			
Petrology					
Thin Section Analysis	------------------------------	-----------------			
XRD and SEM		--------------------------			
Steam Aging		-----------------			
Supplementary Core					
Electrical Properties	-----------------------	-------------------------------	-------------------------------	----------------	
Cation Exchange Capacity		-------------------------------			
Relative Permeabilities @ 100°C/175°C/250°C	------	-------------------------------	-------------------------------	-----------------------------	
Clay Swelling/Fines Mob		----			
Capillary Pressure				----	
Steam Recovery Tests	------	-------------------------------	-------------------------------		
Pore Volume Compressibility		-------------------------------	-----------------		
Thermal Properties			-------------------------------		
Interpretation/Report Preparation			-------------------------------	-----------------------------	----------------------------

FIGURE 2: PROPOSED LABORATORY PROGRAM