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ABSTRACT

The concept of the Vapex (vapour extraction) process has been found promising for the recovery of heavy oil and bitumen in the laboratory study using scaled physical models. In this process a vaporized hydrocarbon solvent, usually ethane, propane or butane is injected into the reservoir using a horizontal well and the diluted (and sometimes deasphalted) oil is produced through another horizontal well by gravity drainage. If a pure solvent is used, the solvent vapour chamber has to be maintained at pressures lower than the vapour pressure of the solvent to prevent the extracted region from being filled with liquid. This presents a problem because, for solvents such as propane and butane, the vapour pressures are often lower than the reservoir pressures.

In the present work the potential for injecting a non-condensable carrier gas along with the solvent to increase the operating pressure is studied. The carrier gas may or may not participate in the leaching process and in the field conditions natural gas may be used as the carrier gas. To achieve the maximum solubility of the solvent at the corresponding temperature the leaching solvent is injected as liquid which is vaporized and carried to the bitumen interface by the carrier gas. The extracted region is left filled with gas and some solvent vapour. This is the concept of the

"Butex" process which has been proved to be effective from the results of experiments presented in this paper.

INTRODUCTION

Recovery of the huge reserves of highly viscous heavy oil and bitumen poses a serious challenge to the engineers. A thermal process, The Steam Assisted Gravity Drainage (SAGD) has been applied successfully for the extraction of these crudes from relatively thicker reservoirs. In thinner reservoirs and in the low porosity carbonate rocks heat losses may prohibit the application of this process. The Vapex process^[1] being nonthermal is free from this problem and can be applied to the vast majority of thin reservoirs containing mostly heavy oil in Alberta and Saskatchewan as well as to the thick bitumen reservoirs. This new process utilizes hydrocarbon solvents to reduce the crude viscosity and is highly energy efficient compared to steam processes^[2].

One important advantage in the Vapex process is the in situ upgrading of the crude by deasphalting in the presence of hydrocarbon solvents, by which the metal, sulphur and nitrogen contents of the crude are reduced. It is predicted that the additions to conversion capacity in the refineries

throughout the world will decrease considerably by the turn of this century^[3]. This and an unfavourable light heavy differential will reduce the marketability of the produced heavy crudes. Any in situ upgrading, such as in the Vapex process, may partially compensate this effect.

From the results of experiments carried out in this laboratory it could be concluded that the Vapex process can be implemented in reservoirs^[2,4,5]. In these studies solvents like propane and butane were maintained at pressures close to their vapour pressures which are much lower than the usual reservoir pressures. In some cases it may be possible to reduce the reservoir pressure within the region from which oil is recovered but this becomes impractical when there is an active aquifer that can invade the recovery region. The gravity driving force in the Vapex process depends on the density difference between two phases and pressures higher than the vapour pressure will liquefy the solvent and reduce the density difference. Also, with a liquid solvent, the reservoir pore volume originally occupied by the produced oil will be left full of liquid solvent rather than vapour. This would greatly increase the net quantity of solvent in the reservoir. With liquified solvent there is also a potential risk of en masse precipitation of asphaltene to form a very viscous semi-fluid phase^[5] this may plug the reservoir and impair the flow of diluted oil. In some of the reservoirs the pressure is close to the vapour pressure of ethane at the reservoir temperatures. A group of researchers at Imperial Oil has reported successful use of ethane for the recovery of Cold Lake bitumen using a cyclic solvent stimulation process^[6]. However, studies in this lab shows that the production rates with ethane are lower than those with propane and butane^[7].

One practical way of increasing the operating pressure while keeping the solvent vaporized is to use a mixture of propane or butane with non-condensable carrier gases eg. methane, ethane, nitrogen, carbon dioxide etc. Results of experiments using a Hele-Shaw cell for the extraction of Peace River bitumen with mixtures of various solvent vapours have shown that the extraction rate using mixture of two solvents is in between the extraction rates with the pure solvents^[8]. The presence of a low solubility carrier gas at higher concentration is expected to reduce the production rate. However, with the carrier gas continuously replenished by evaporation of liquid solvent a high concentration of the solvent can be achieved at the solvent bitumen interface. These ideas are incorporated in the concept of a new process, "Butex" as presented below.

THE CONCEPT OF THE BUTEX PROCESS

Figure 1 explains the concept of the Butex process, in which the leaching solvent is injected in the liquid phase along with the high pressure carrier gas. The liquid solvent

evaporates in the reservoir near the injector and the vapour is carried by the gas to the bitumen. Vaporized solvent dissolves in the bitumen and drains down and flows to the production well. Due to the presence of liquid solvent the carrier gas is continuously saturated with the solvent vapour. This high pressure gas may or may not participate in the extraction process. Eventually the gas reaches the top of the chamber and much of the remaining oil drains by gravity towards the bottom of the reservoir. Finally the pore space occupied initially by oil remains full of gas.

Earlier experimental results^[8] proved that in a reservoir with bottom water layer or horizontal fracture the Vapex process yields higher production rate in upward leaching of heavy oil or bitumen compared to the sideways leaching which is the only option otherwise. Both configurations were used in the experiments described in this paper.

The presence of liquified solvent may cause plugging of the reservoir near the injection well due to excessive deasphalting. It was observed in experiments using Hele-Shaw cells^[4] that the extent of deasphalting is less in the experiments using butane as a solvent than in those using propane. Thus it is expected that with liquid butane the chance of plugging the reservoir is lower. Liquid butane with any suitable carrier gas may be used for this extraction and hence the name "Butex" - butane extraction. However propane was also used in some later experiments and these also proved to be successful. In the experiments described below nitrogen was used as the carrier gas. In some of the latest experiments methane was used as a carrier gas and it is anticipated that in many field applications natural gas would be used.

In the Butex process a slow stream of gas has to be produced along with oil to ensure a continuous flow of the carrier gas. In the experiments with upward leaching this will also help in maintaining the communication path between the injector and producer through the water and assists in the spreading of the solvent vapour underneath the bottom of the entire bitumen layer. Results of similar experiments using pure solvents showed that continuously producing a small amount of gas enhanced the rate^[6]. Essentially this creates a small potential gradient along the flow path, sufficient to draw some vapour through the bottom water layer. In the sideways leaching also this potential gradient may help in the production. In the Butex process the produced gas will be mostly the carrier gas associated with a small fraction of solvent vapour which will be recycled ultimately in the field condition.

EXPERIMENTAL

The ability to observe the progressive development of the vapour chamber, asphaltene precipitation and drainage paths in real time during the course of recovery experiments helps significantly in interpretation of test

results. Thus a windowed, visual scaled model was designed for the experimental pressure. As higher operating pressure requires a bulkier construction, the design pressure for the cell was chosen to be 1.379 MPa (200 psig). Even with this design pressure the weight of the complete assembly is about 150 kg and it requires a hoist to move the cell in the laboratory.

Components of the high pressure cell

The sand pack is confined in the cell cavity by a front and a back plate. The 38.1 mm thick Perspex front plate of dimension 806×307 mm was supported by a 50.8 mm thick steel plate with a set of apertures cut in it for viewing the process. The cell cavity and the back plate are made of 31.8 mm thick phenolic sheets. The cell cavity is of dimension $706.4 \times 205 \times 31.8$ mm. The back phenolic sheet is supported by a 25.4 mm thick solid steel plate. With this design the maximum deflection in the Perspex was computed to be 0.001 inch ($25.4 \mu\text{m}$) at a test pressure of 200 psig (1.379 MPa) and this value of deflection was indeed observed when the cell was tested under pressure.

There are five ports on the top and five ports on the bottom of the cell cavity, all fitted with necessary fittings and valves. Usually the cell is filled with oil through the top five ports, with the cell in the upside down position. Any of these ten ports can be used as an injector and any of the bottom five ports can be used as a producer. There are six thermocouples in the cell cavity that measure temperatures in the packed bed at different locations.

Experimental Set-up

The experimental set-up used is shown in Figure 2. The scaled physical model is weighed by a highly sensitive load cell. During the experiment the weight is recorded at pre-set short time intervals. An ISCO syringe pump is used to inject liquid solvent at a constant rate provided that the pressure is less than the pre-set limit. It is possible to set the pumping rate, however as soon as the set pressure is exceeded the pump stops and it is sometimes difficult to maintain a constant injection rate. Nitrogen is drawn through a regulator from a cylinder; the pressure is set to the desired operating pressure and prior to injection nitrogen is passed through a mass flow meter.

Produced oil drains by gravity to a collection pot; oil level in the pot is indicated in an attached transparent nylon tubing. Depending on the level the production is removed in glass bottles. The solution gas and the free gas volumes are measured in two bubblers.

Kithley-Metrabyte DAS-8PGA and EXP-16 data acquisition systems in combination with the software, Labtech Note Book are used to read, display and record experimental data. The following data are recorded :

(a) Output voltage from the load cell weighing the packed

cell amplified by passing through an on-line, voltage amplifier. This system is highly sensitive and can register the changes in weight even by a few grams. Using the software the voltage is instantly converted to weight and displayed on a computer terminal.

- (b) Output from seven thermocouples, six of them measuring temperatures inside the cell, one measuring the ambient temperature. Data are displayed and recorded in terms of temperature.
- (c) Signal from a PSI-TRONIX strain gage pressure transducer (PSI-420) attached to the injection line. The output current from the pressure transducer is measured as the resultant voltage drop across a resistor. This voltage is calibrated against pressure. Data are displayed and stored in terms of pressure.
- (d) The output voltage from the mass flow meter measuring the nitrogen flow rate is recorded and converted to the flow rate using calibration data. This gives the instantaneous nitrogen injection rate.

Experimental Procedure

The following gives the general procedure used in all of these experiments although there were some modifications in different experiments. Details of each experiment are described with experimental results.

The cleaned cell is placed on the load cell and the output voltage from the amplifier is noted using a multimeter. Applying known loads on the cell the output voltage is calibrated for its equivalent loads. The cell is then removed from the load cell, turned 90° to stand on its vertical edge, fixed on a steel frame and packed with the desired sand using a vibrator attached to the steel frame. To get a better packing air is passed downwards through the packing; injected through the top ports and allowed to come out through the bottom ports.

The permeability of the sand pack is measured passing air at a measured, low flow rate through the packing from top ports to bottom ports and measuring the pressure drop across two horizontal planes located near the middle of the cell to avoid the end effects. The packed cell is then placed on the load cell and the change in voltage gives the weight of sand in it. The cell is again fixed on the steel frame to hold it in vertical position and flooded with water from the bottom. Excess water is passed through the cell until the outlet stream becomes free of visible air bubbles. The water filled cell is again weighed on the load cell. Porosity of the cell is determined from the amount of water in the cell. The cell is now ready for filling with oil and is fixed on a trolley and placed inside an oven. Water is displaced with the test oil. The oil is heated to about 60°C to reduce its viscosity. To increase the rate of displacement a low air pressure is applied above the hot oil in the pot containing oil. The displaced water is collected in a jar and

the volume of water displaced gives the volume of oil injected in the cell. After the displacement is completed to the desired extent (in some experiments oil is filled partially to form a bottom water layer about 25 mm thick) the water outlet valve is shut off and the cell is allowed to cool down to the ambient temperature. During this period the oil pot is left connected to the cell so that any shrinkage due to cooling can be filled with oil.

The oil filled cell is placed on the load cell. To get better accuracy the load cell is again calibrated over a small span of output voltage. All components of the data acquisition system are organized and connected to the computer. Initial settings and calibration of the data acquisition channels are completed and data acquisition and display started.

The experiment starts with the injection of nitrogen into the cell at a controlled rate until the pressure reaches the operating pressure. The production valve is then cracked open and nitrogen breaks through almost immediately. the pressure in the collection pot rises quickly to the operating pressure. Water from the bottom layer is produced during this pressurization with nitrogen. Liquid butane and nitrogen are then injected through the same injection point. At this pressure and the ambient temperature of about 22°C nitrogen was observed to bubble through liquid butane in the vicinity of the injection well.

A slow stream of gas is drawn continuously from the top of the collection pot; this ensures the flow of the carrier gas through the packed bed. This gas is collected in a bubbler and the volume measured.

From the collection pot the produced oil is emptied from time to time to production bottles by opening the connecting valve cautiously such that the drop in pressure is not transmitted to the cell causing a surge in oil production. As the oil drains to the production bottle its pressure is reduced to atmospheric pressure and a part of the solvent dissolved in the produced oil boils off in the form of vapour. This vapour is collected in a bubbler by displacing a column of water and the volume of the vapour noted. The production bottles are weighed with the lids on and then the lids are left slightly loose. This allows more dissolved solvent to escape later and the bottles are reweighed until an almost constant value is reached. The amount of solvent so vaporized is noted. These weights are used to make a material balance on the solvent injection and production.

RESULTS OF BUTEX EXPERIMENTS

In this paper results of eight experiments are presented; in six of these the injection wells were located near the water oil contact in a simulated bottom water layer and oil was leached by solvent vapour rising upward. These experiments are numbered with a prefix 'U'. In the rest of

these experiments injection wells were located at the top of the model and oil was extracted by sideways leaching; accordingly these experiments are numbered with a prefix 'S'. Experimental conditions of all experiments are presented in Table 1. Results of individual experiments are described below.

Experiment # U1

This experiment was carried out with Peace River bitumen (viscosity 138300 mPa.s at 20°C) using a 30-50 mesh Ottawa sand packing (permeability $43.5 \mu\text{m}^2$). Due to some problem in filling the low permeability cell with the high viscosity oil a uniform water layer as planned could not be formed. In this experiment nitrogen and butane were injected through different ports located near the water oil contact and injection of both fluids started almost simultaneously. The pressure was regulated to 0.814 MPa and the average temperature was 21.5°C. Butane injection rate was controlled to about 25 g/hr, decided arbitrarily in anticipation of a high production rate. Nitrogen injection rate was not measured in this first experiment; from the amount of gas collected in the bubbler it was estimated to be about 1.5 g/hr.

Initially the free water was displaced from the water layer and in the first 5 hours 93 g of water were produced along with 10 g of oil. In the next 7 hours oil was produced at a rate of 13.3 g/hr. It was obvious that the solvent injection rate was much higher than practical in field operation. Subsequently the butane injection rate was reduced to 5.0 g/hr and the production rate dropped to about 8.0 g/hr. Probably the solvent injection rate was too high and the injection rate of nitrogen was too low and at the later stage the communication path, formed initially, was filled with mostly liquid butane and diluted oil instead of vapour, leading to a low gravity drainage rate. When the cell was opened after the experiment there was no indication of consolidation in the sand matrix except in a small region close to the injector well. Although the experiment was not considered successful it indicated that use of a solvent in the liquid phase in combination with a non-condensable gas is feasible.

Experiment # U2

Figure 3 presents the results of Experiment # U2 carried out with Lloydminster oil using packing with a permeability of $194.4 \mu\text{m}^2$. The experiment started with injection of only nitrogen into a more or less uniform water layer. Slowly the pressure was raised to the operating pressure (0.779 MPa) and some water was collected as production. Then butane and nitrogen were injected at average rates of 19.4 g/hr and 2.2 g/hr. The vapour was rising to the top of the chamber through the heavy oil and the diluted oil was draining downwards. It was observed that the entire

oil bank was moving down leaving a vapour chamber at the top. The process was smooth and continued at a rate of 46.9 g/hr initially for a short period and then at about 36.0 g/hr as the height of the oil bank was falling. The average rate over the entire time period was 41.7 g/hr ($0.0315 \text{ m}^3/\text{day m}$).

The original oil viscosity was 9350 mPa.s. There was considerable improvement in the viscosity of the produced oil as presented in Figure 4. There was no consolidation in the bed except for a small zone near the injection well and this did not prevent flow. Thus it was shown that the concept of Butex could be made to work, at least in a laboratory model.

Experiment # U3

The objective of this experiment was to study the effect of butane injection rate on the production rate from the Butex process. This experiment was carried out with conditions almost identical to those used in the experiment # U2, except with a different butane and nitrogen injection rate. The butane injection rate was about 12.5 g/hr and nitrogen went faster (about 3.75 g/hr). The average production rate was 28.2 g/hr. The experiment started with a uniform thin bottom water layer. Vapour rose to the top and the vapour chamber on top of the oil bank grew as the oil drained.

The shape of the solvent chamber as viewed through the transparent windows gave an impression that the solvent vapour and nitrogen, instead of passing through the bottom water layer to the production well was bypassing through the vapour chamber at the top of the cell to the production well. The probable reason for this bypassing might have been slightly loose packing at the producer end which was at the top of the cell while filling with sand. It was thought that the bottom water layer might have been filled with liquid and communication through it became lost and solvent vapour followed the path of the least resistance.

Experiment # U4

Experiment # U4 was a repetition of experiment # U3 taking special care to get a perfect packing of the cell. In this experiment the cell permeability was $191.1 \mu\text{m}^2$; temperature and pressures were similar to that of experiment # U3. Results of this experiment are presented in Figure 5. The butane injection rate was 11.4 g/hr and nitrogen was injected at an average rate of 4.2 g/hr. The experiment went as desired and there was no indication of bypassing as in the experiment # U3. Figure 6 presents two photographs taken during this experiment. The top picture presents the bottom water layer at the beginning of the experiment and the bottom picture shows the extraction chamber after 19.25 hrs from the beginning of the experiment. At this stage vapour was rising to the top of

the chamber through the heavy oil and the diluted oil was draining downwards. It was observed that the entire oil bank was moving down leaving a vapour chamber at the top.

In this experiment the production rate was 28.2 g/hr initially, followed by 18.5 g/hr as the oil level was falling in the bed. A comparison of the injection and production rates in experiments U2 and U4 shows that the production rate was reduced as the butane injection rate was lowered.

Experiment # U5

The objective of this experiment was to investigate the rise of a vapour chamber in a crude of higher viscosity. Cold Lake bitumen of viscosity 65000 mPa.s at 20°C was used in this experiment with a packing permeability of $186.8 \mu\text{m}^2$. Butane was injected at an average rate of 12 g/hr and the injection rate of nitrogen was about 4.6 g/hr. The vapour was observed to rise through the oil and as the oil was draining, a vapour chamber formed on top of the oil layer similar to that in the experiments with Lloydminster oil. The oil was produced at a rate of 9.5 g/hr for the first few hours. In the later part of the experiment the production rate was low. The reason for this may be the higher injection rate of solvent compared to the rate of oil production. This probably resulted in accumulation of liquid butane in the bottom layer reducing the gravity drainage rate. Although it was thought that liquid butane may have caused deasphalting and plugging, when the cell was taken apart no consolidation was observed in the sand pack and this possibility was ruled out.

Experiment # U6

All of the above Butex experiments were carried at a pressure 0.779-0.814 MPa. In the actual field operations the pressure may be higher which can be easily achieved by increasing the carrier gas pressure. However, with increase in pressure the diffusion coefficient in the gaseous phase decreases proportionately to the reciprocal of the pressure. Since in this process the butane vapour has to reach the interface by diffusing through the carrier gas the gas phase resistance to diffusion may play a significant role in controlling the process at higher pressure. Hence it is necessary to study the effect of operating pressure on the process performance. In the experiment # U6 the pressure was controlled to 0.434 MPa (50 psig). Results of this experiment are presented in Figure 7. Butane injection rate was maintained at 24.8 g/hr and nitrogen was injected at a rate of 2.9 g/hr. The average production rate was 40.5 g/hr compared to 41.7 g/hr in the experiment # U2 where the pressure was 0.779 MPa. This shows that, in this range, the operating pressure does not have a significant effect on the production rates. However, experiments must be carried out in the range of practical reservoir pressures

to confirm the effect of operating pressure.

Experiment # S1

As it is observed in the Butex experiments that extraction with liquid butane in the presence of a high pressure gas does not consolidate and plug the sand matrix the same principle can be used in spreading chambers also. This may be useful in the reservoirs without bottom water layer. This idea was tried in experiment # S1. The experiment started with an oil flooded cell with an almost uniform water and oil saturation (79.1%) everywhere in the pack. Initially Butane with nitrogen was injected at the top of the cell vertically above the production well. The pressure was maintained at 0.779 MPa. At this pressure most of the butane remains in the liquid phase and falls through the vapour chamber to the interface and extracts bitumen. As the chamber spread side ways the butane injection point was moved along the top of the reservoir to promote liquid butane draining along the entire interface. Results of this experiment are presented in Figure 8. Oil was produced at a rate of 22.4 g/hr for a butane injection rate of 9.5 g/hr. Nitrogen was injected at a rate of about 1.8 g/hr. Hence it is possible to use the concept of the Vapex process even by injecting the solvent in liquid phase along with a non-condensable gas. The vapour chamber is maintained by the non-condensable gas maintaining the high density difference of a vapour-liquid system yielding a higher gravity drainage rate and minimizing the net solvent consumption.

Experiment # S2

In the experiment # S1 the movement of the injection point in practical sense is equivalent to a set of closely spaced injection well along the top of the reservoir and for a thin reservoir this concept may be prohibitively costly to put into practice. Although offset injection may be possible, achieving initial communication was a concern. The possibility of using propane was also to be tested. In the experiment # S2, nitrogen and propane were injected simultaneously using an injection well placed at the top corner of one end of the packing and oil was produced at the bottom corner of the other end as shown in Figure 9.

Average temperature of the cell during the experiment was 21.5°C. The vapour pressure of propane at the same temperature is 0.879 MPa. Due to the limitation of the cell the operating pressure was maintained at 0.959 MPa. Thus the extraction was being carried out using propane injected as a liquid; the vapour chamber was maintained by nitrogen.

Figure 9 presents the experimental results. The experiment started with injection of nitrogen gas at the operating pressure. Nitrogen broke through after a short time; the amount of oil produced during this period was very small. This was followed by injection of nitrogen and

propane together, rates being 1.25 g/hr and 15 g/hr respectively. For a very short period after the injection of propane started the oil was produced at a higher rate (50 g/hr) indicating that propane was invading through the fingers created by nitrogen and contacting oil at a larger interfacial area. However as those fingers slowly filled with diluted oil the rate slowed down to the usual gravity drainage rate. During the refilling of the ISCO pump, propane injection was stopped between the points X and Y shown in the figure. However the production continued at the uniform rate at 25 g/hr, presumably due to the presence of accumulated propane in the chamber.

Figure 10 presents a photograph taken during this experiment that shows the extraction chamber seen through the viewing windows of the cell. Well configurations and experimental time are indicated on the photograph. Black bands in the extracted zone are the deposited asphaltenes and these were probably caused by the higher concentrations of propane during certain periods. However, no flow-obstruction problem was encountered and the production was steady as is clear from the results presented in Figure 9. Viscosities of the produced oil measured at 20°C, presented in Figure 11, show considerable in situ upgrading due to deasphalting with propane.

Results of the experiments using The Butex concept are summarized in Table 2.

CONCLUSIONS

1. It is demonstrated in the results of the experiments presented in this paper that the concept of the Butex is suitable for further development.
2. The production rate depends on the solvent injection rate. A minimum amount of solvent is required to render the oil mobile. However, higher injection rate may lead to accumulation of liquid solvent in the chamber affecting the production rates. An optimum solvent injection strategy is necessary for a successful field operation. Our latest experiments (to be published soon) show that higher production rates can be achieved with much lower solvent injection rate.
3. Both propane and butane are suitable solvents. With butane the solvent hold up is more. With propane the improvement of the product quality is higher giving propane an edge over butane.
4. Operating pressure did not affect the production rate significantly in these experiments which indicates that gas phase diffusion resistance is not important in the pressure range employed.
5. This concept can be implemented for the extraction of reservoirs underlain by aquifer using upward leaching configuration. In absence of aquifer sideways leaching is equally possible.

NOMENCLATURE

$\Delta\rho$	density difference between solvent and bitumen (kg/m^3)
μ	viscosity ($\text{mPa}\cdot\text{s}$)
D	Diffusivity (m^2/s)
g	acceleration due to gravity (m/s^2)
H	reservoir height (m)
k	permeability (μm^2)
l	length (m)
L	length of horizontal well (m)
q	volumetric flow rate (m^3/s)
t	time (s)
W	spacing between the injector and the producer (m)

Subscripts

<i>cum</i>	cumulative
<i>F</i>	field
<i>M</i>	model

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APPENDIX

SCALING THE EXPERIMENTAL RESULTS

To obtain meaningful predictions the physical model should be suitably scaled for field conditions. Scaling of the physical model results involves the following principles:

Geometric Similarity

Since the process uses a pair of horizontal wells, a cross section perpendicular to the well should be geometrically similar in both physical model and reservoir. Thus,

$$\frac{H_F}{H_M} = \frac{W_F}{W_M} \quad (1)$$

The cumulative volume of oil produced in the field and model at comparable times are proportional to the volume of reservoir included in the pattern and the volume of the model

$$\frac{q_{cum,F}}{q_{cum,M}} = \frac{H_F W_F L_F}{H_M W_M L_M} = \frac{H_F^2 L_F}{H_M^2 L_M} \quad (2)$$

where L_F and L_M are lengths of horizontal wells in the model and field.

Dynamic Similarity

Distance of solvent penetration due to molecular diffusion in the physical model (l_M) and in the reservoir (l_F) respectively in the equivalent model time (t_M) and reservoir time (t_F) can be related by the dimensionless

numbers as follows:

$$\frac{Dt_M}{l_M^2} = \frac{Dt_F}{l_F^2} \quad (3)$$

since molecular diffusivity may be considered to be same in the model and field. Considering the fact that the l_M and l_F should be proportional to the model and reservoir dimensions H_M and H_F rearrangement of equation (3) gives

$$t_F = t_M \left(\frac{H_F}{H_M} \right)^2 \quad (4)$$

The drainage rate at any point in the model and reservoir is given by Darcy's law as

$$q = \frac{dq_{cum}}{dt} \propto \frac{kHL}{\mu} \Delta \rho g \quad (5)$$

Since the density difference, viscosity and gravity will remain same for the same bitumen-solvent system in physical model and field conditions then

(6)

Using equations (2) and (4) to replace the ratios of time and cumulative production in equation (6) and rearranging we get

$$k_F H_F = k_M H_M \quad (7)$$

In situations where the bitumen is extracted by upward leaching the darcy flow area (HL) in equation (5) should be replaced by WL and the results for these configurations should be scaled using the relationship

$$k_F W_F = k_M W_M \quad (8)$$

Either of equations (7) and (8) dictate the choice of permeability of the packing in the physical model required to satisfy both geometric and dynamic similarity. If this condition is satisfied equation (6) also shows that

$$q_F L_F = q_M L_M \quad (9)$$

that is the production rate per unit length of the horizontal well (m^3/m day) is same in the model and in the field.

The capillary effect has been neglected in the analysis given above. Capillary rise in the sand matrix may reduce the effective head for the gravity drainage. However, it was shown^[7] that the capillary effect is relatively more prominent in the physical model experiments than in the field operation. Hence the predictions from the results of experiments carried out in this model are conservative.

Examples

For the upward leaching of Peace River bitumen in

Experiment # U1, the distance between the injector and producer well was about 0.7 m. The product $k_M W_M$ is $30.45 \mu m^2 \cdot m$ which by equation (8) should be same as is $k_F W_F$. Thus the results of this experiment represents, for example, extraction in a $0.5 \mu m^2$ vertical permeability using a pair of horizontal wells separated by a distance of 60 m. It should be noted that by geometric similarity the model then represents only a 17 m thick reservoir whereas the Peace River reservoir is about 40 m thick. Since the extraction rate in the upward leaching mode is independent of the reservoir height and the extraction front moves at a constant rate^[9] until the front reaches to the top of the reservoir, thickness does not affect the scaling of the extraction rate. Higher thickness will result in longer production life of the project.

Similarly in the experiment # U2 Lloydminster oil was extracted from a packing of permeability $194.4 \mu m^2$, $k_M W_M$ is about $136 \mu m^2 \cdot m$ which may be represented by a well spacing of about 140 m in $1 \mu m^2$ (vertical permeability) reservoir. This kind of well separation is possible in the heavy oil reservoirs where achieving initial communication may not be a problem.

In the experiments # S1 and S2 Lloydminster oil was extracted by side ways leaching from a packing of permeability about $195 \mu m^2$; $k_M H_M$ is about $40 \mu m^2 \cdot m$ which may be represented by 10 m thick reservoir with $4 \mu m^2$ horizontal permeability. This type of reservoirs are indeed available in the Lloydminster area.

Table 1. Experimental conditions in Butex experiments

Experiment No.	k μm^2	ϕ	Crude	S_o	Solvent	Pressure (MPa)	Average Temperature ($^{\circ}\text{C}$)	Configuration
U1	43.5	0.31	PR ¹	0.80	butane + N ₂	0.814	21.5	Upward Leaching
U2	194.4	0.31	LM ²	0.89	butane + N ₂	0.779	22.0	Upward Leaching
U3	191.5	0.35	LM	0.86	butane + N ₂	0.779	21.7	Upward Leaching
U4	191.1	0.33	LM	0.85	butane + N ₂	0.779	21.2	Upward leaching
U5	186.8	0.33	CL ³	0.88	butane + N ₂	0.779	21.6	Upward Leaching
U6	192.4	0.32	LM	0.91	butane + N ₂	0.434	21.6	Upward Leaching
S1	195.8	0.37	LM	0.79	butane + N ₂	0.779	21.8	Top Injection (Well moved)
S2	194.0	0.33	LM	0.93	propane + N ₂	0.959	21.5	Top Injection

- 1 Peace River bitumen
- 2 Lloydminster Tangleflags heavy oil
- 3 Cold Lake bitumen

Table 2. Results of Butex experiments

Experiment No.	k μm^2	Crude	Configuration	Solvent Injection rate(g/h)	Nitrogen Injection rate(l/h)	Production rate (g/h)	kW or kh ($\mu\text{m}^2 \cdot \text{m}$)	Field Production ($\text{m}^3/\text{m} \cdot \text{day}$)
U1	43.5	PR ¹	Upward Leaching	255	1.2	(a) 13.3 (b) 8.0	30.7	0.010 0.006
U2	194.4	LM ²	Upward Leaching	19.4	1.6	(a) 46.9 (b) 36.0	137.3	0.0354 0.0272
U3	191.5	LM	Upward Leaching	12.5	3.0	28.2	135.3	0.0213
U4	191.1	LM	Upward leaching	11.4	3.4	(a) 28.2 (b) 18.5	135.0	0.0213
U5	186.8	CL ³	Upward Leaching	12.0	3.7	9.5	132.0	0.0072
U6	192.4	LM	Upward Leaching	24.8	2.3	40.5	135.9	0.0269
S1	195.8	LM	Top Injection (Well moved)	9.5	1.5	22.4	40.1	0.0169
S2	194.0	LM	Top Injection	15	1.0	(a) 50.0 (b) 25.0	39.8	0.038 0.019

(a), (b) represent different phases of production

1 Peace River bitumen

2 Lloydminster Tangleflags heavy oil

3 Cold Lake bitumen

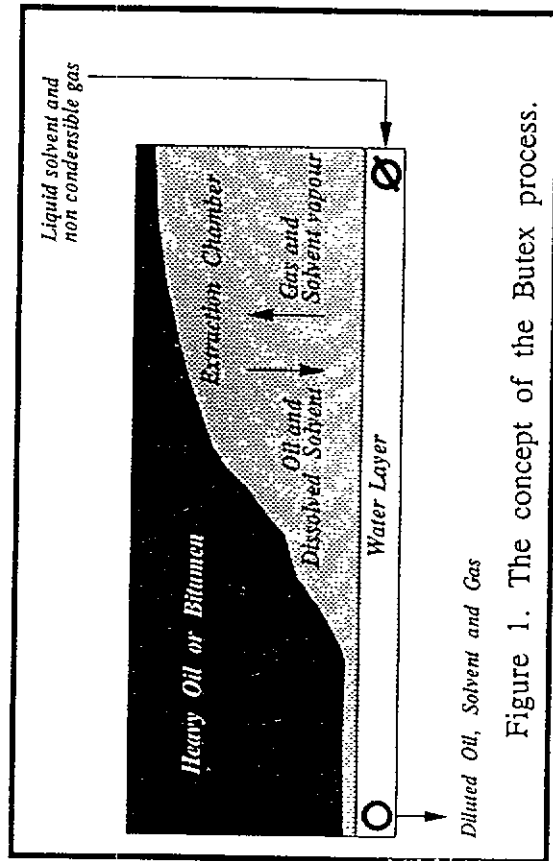


Figure 1. The concept of the Butex process.

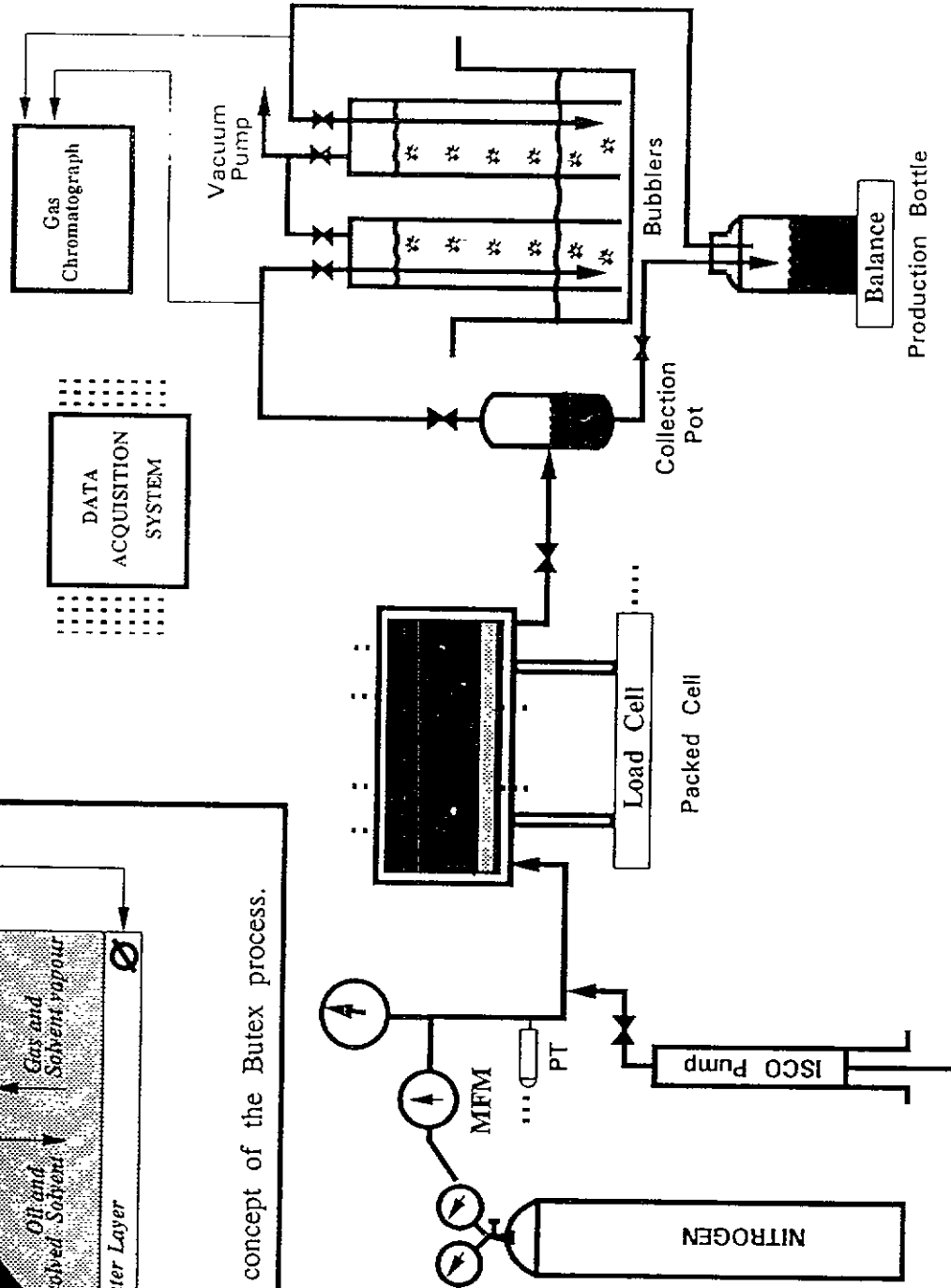


Figure 2. Experimental set up used in the Butex experiments.

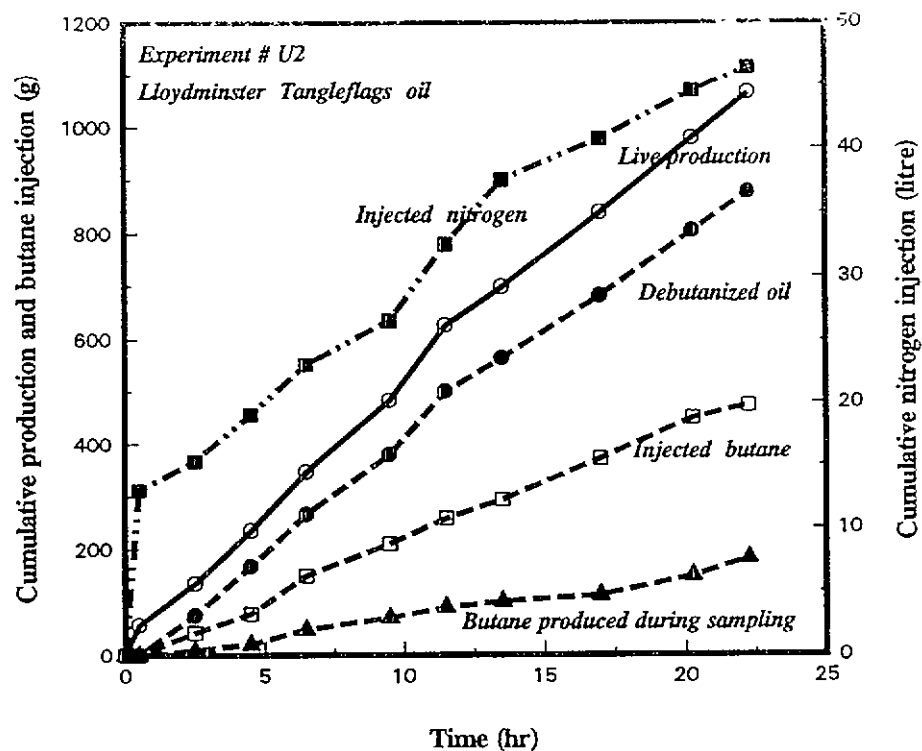


Figure 3. Butex: Upward leaching with butane and nitrogen at higher pressure

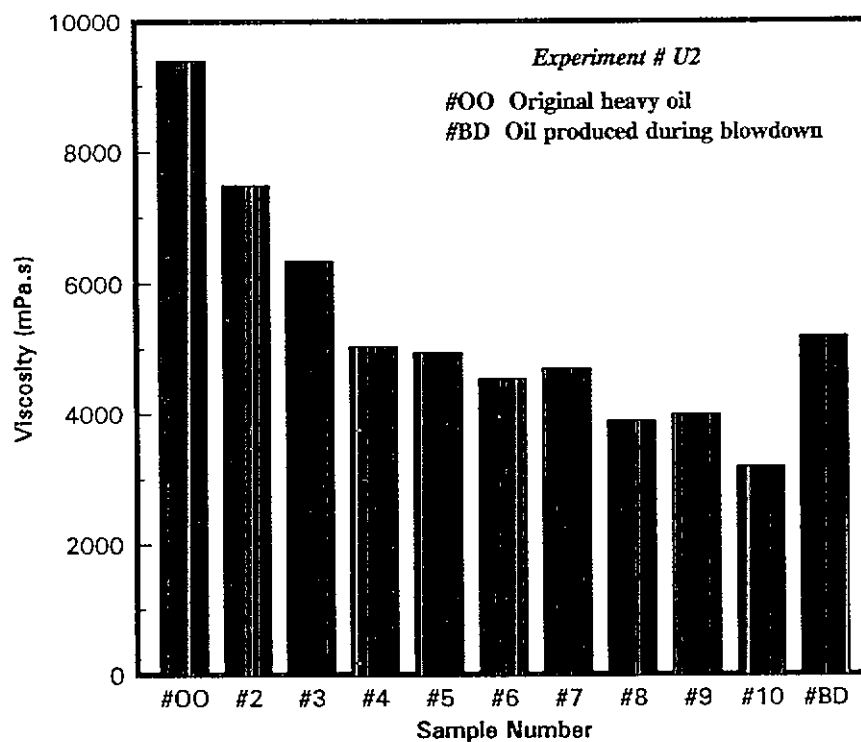


Figure 4. Viscosity of the original and produced oil in Experiment # U2.

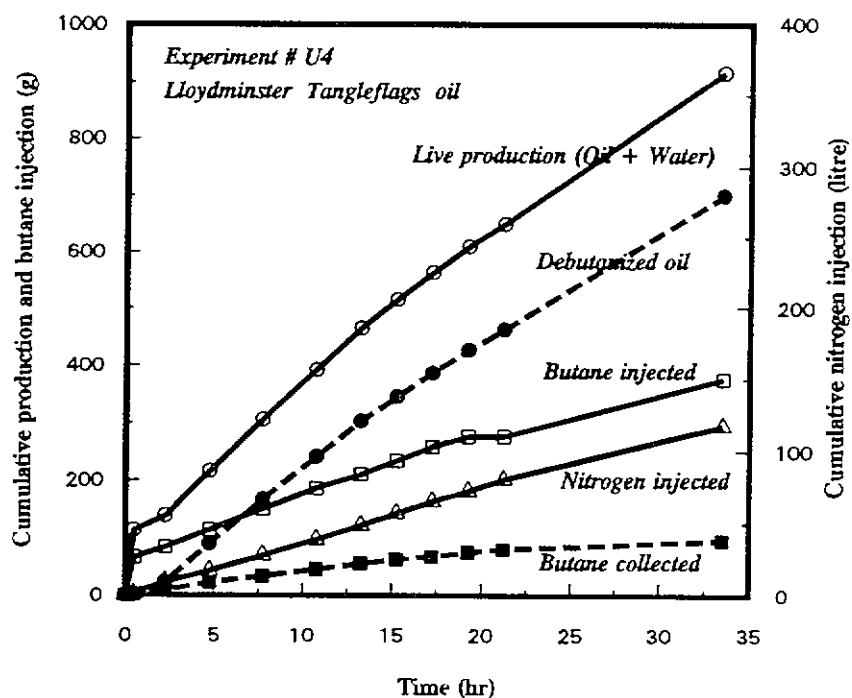


Figure 5. Extraction using the Butex with lower rate of butane injection.

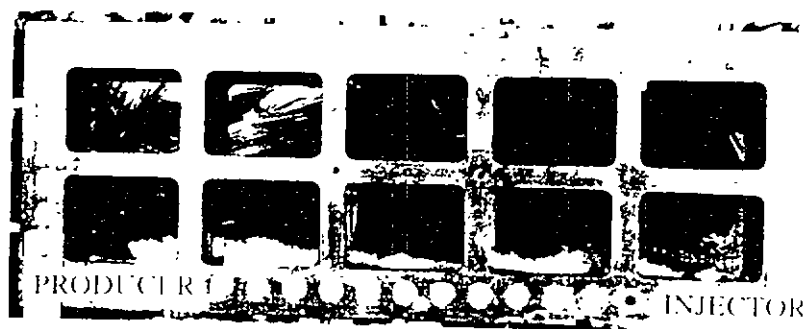
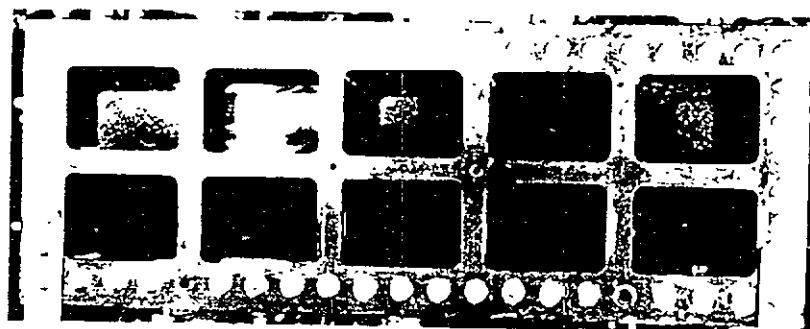


Figure 6. Photographs taken during experiment # U4

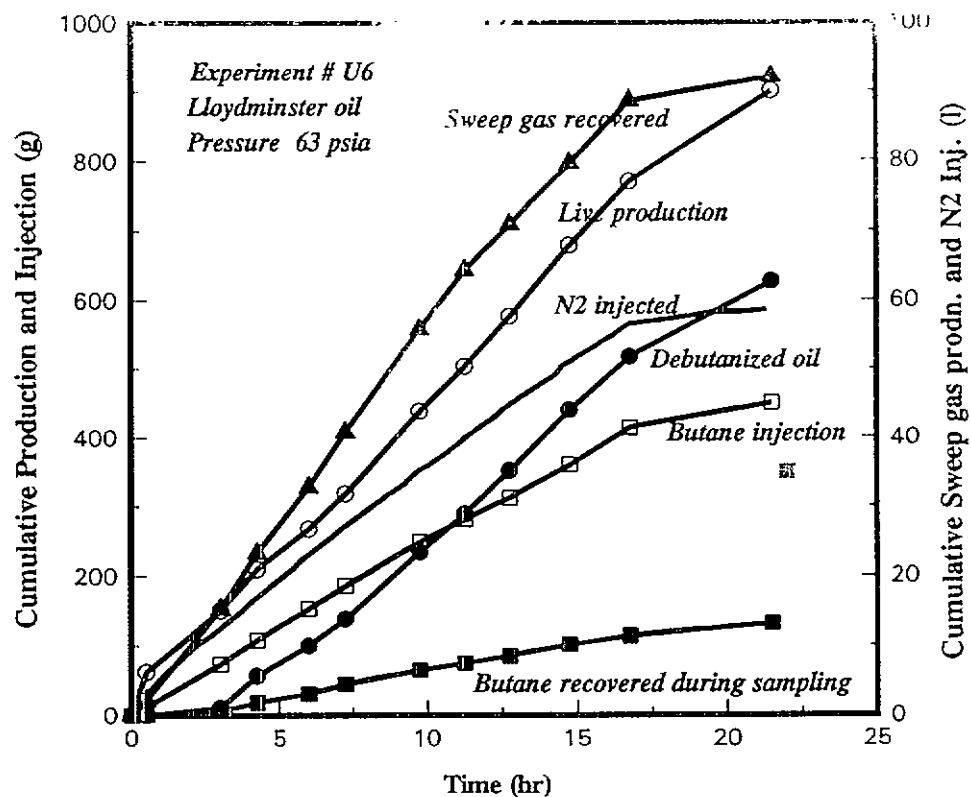


Figure 7. Performance of Butex at a lower pressure.

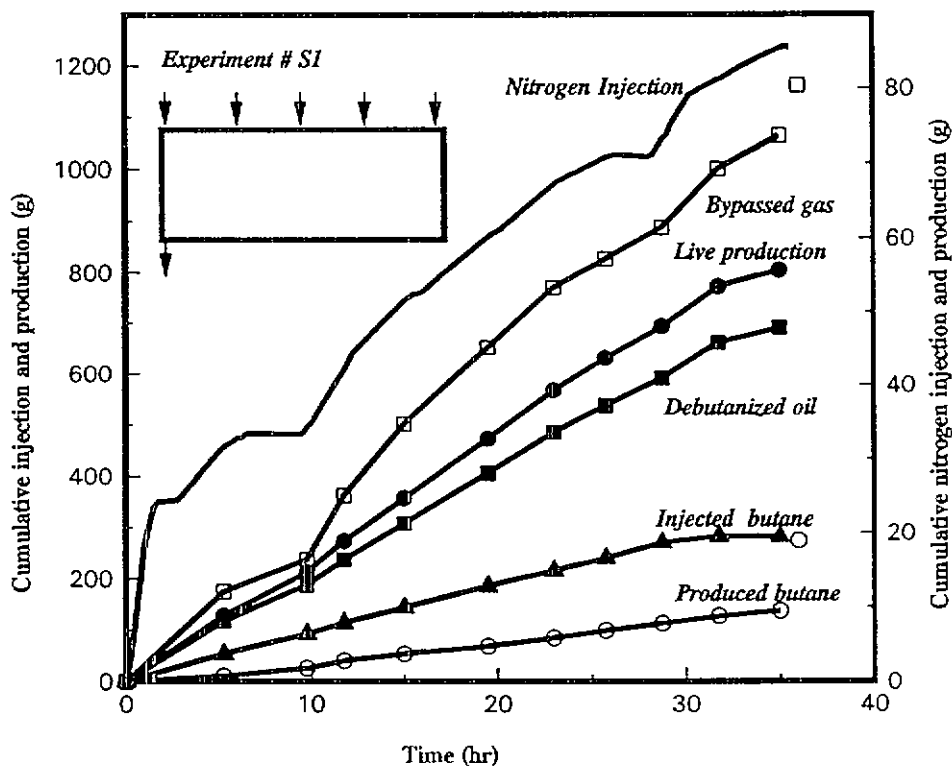


Figure 8. Extraction of Lloydminster oil with liquid butane and nitrogen.

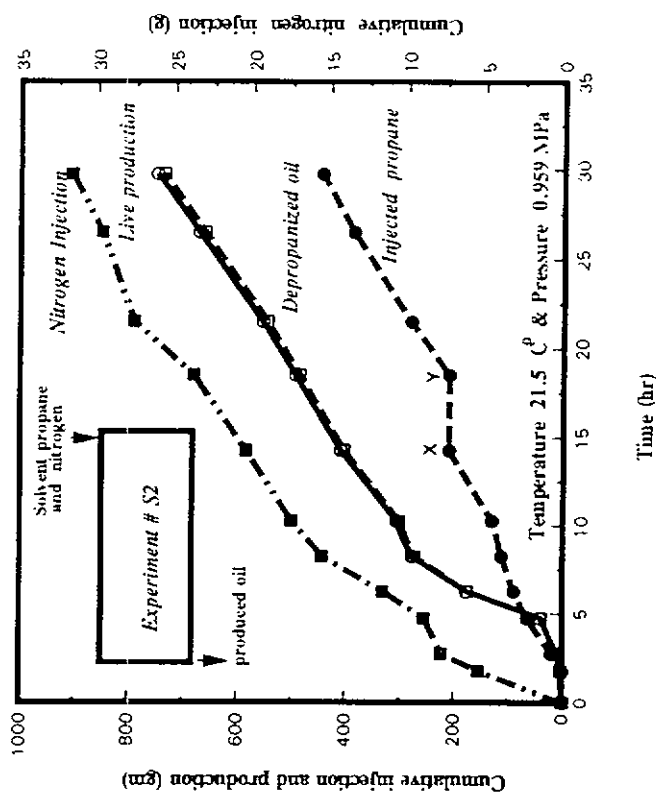


Figure 9. Extraction with propane and nitrogen.

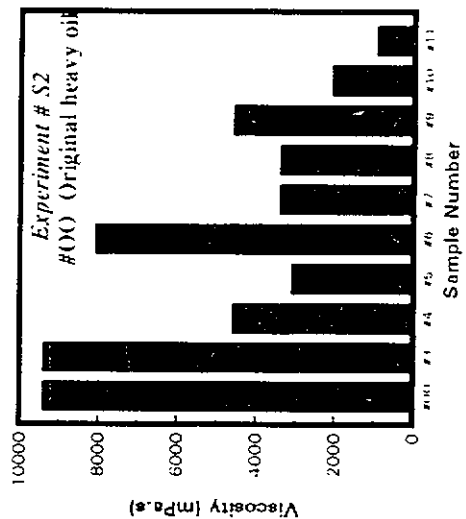


Figure 11. In situ upgrading with propane in experiment # U2.

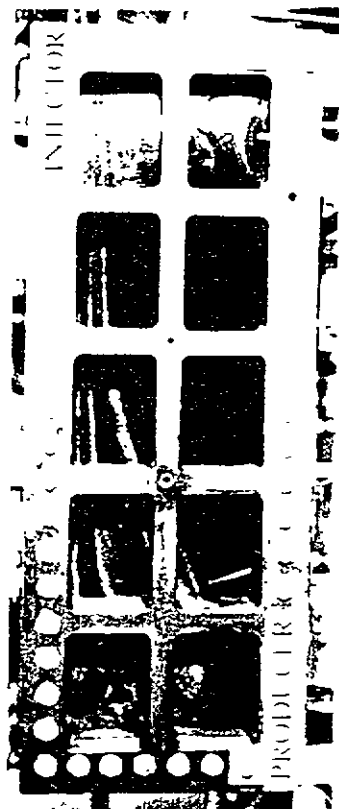


Figure 10. Photograph taken during the experiment # S2.