

# A new process (VAPEX) for recovering heavy oils using hot water and hydrocarbon vapour

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## ABSTRACT

*There are extensive deposits of heavy oils in Saskatchewan and Alberta which can only be recovered with low efficiency by conventional methods. Thermal recovery processes using steam, although effective, are uneconomic in many of the Lloydminster-type reservoirs because the deposits are relatively thin and heat losses to the overburden and underburden are excessive.*

*A new idea is to use a solvent, such as propane, in the vapour phase which can form a vapour-filled chamber within the reservoir. Vapour dissolves in the oil around the chamber and the resulting solution drains, driven by gravity, to a horizontal production well placed low in the formation. The solvent vapour, at or near its dew point, is injected simultaneously with hot water from a horizontal well located at the top of the reservoir. The temperature and flow rate of the water are chosen so that the reservoir temperature is raised to the range of only 40°C to 80°C. As the diluted bitumen drains toward the production well, it interacts with hot water and some propane re-distills upward to dilute further bitumen. There is, thus, a transport of heat from low down in the reservoir to the upper reaches by the evaporation of propane near the bottom and its condensation (dissolution) at the top. This mechanism causes the heat in the water to be distributed through the reservoir, in particular, laterally away from the point of injection.*

*Results are presented that show the gas/oil and water/oil ratios and the additional oil recovery from a vertical, two-dimensional scaled reservoir model due to propane injection near the end of a hot waterflood. The essential feature of the recovery mechanism and the process conditions are discussed.*

## Introduction

There are extensive deposits of heavy oils in Saskatchewan and Alberta which can only be recovered with a low recovery efficiency by conventional methods. Primary recovery in the best of these heavy oil reservoirs can yield about 6% of the original-oil-in-place. Waterflooding can improve the recovery but only to an extent of 1% to 2% because of the adverse mobility ratio.

The recovery concept, which is described here, is closely related to the steam-assisted gravity drainage (SAGD) Process which has been discussed in the literature<sup>(1-8)</sup>. In the SAGD process, a growing steam chamber forms as steam is injected into the reservoir and steam flows continuously to the perimeter of the chamber where it condenses and heats the surrounding oil. The heated oil drains, driven by gravity, to a horizontal well located at the base of the

reservoir. This process is effective and can be economic if the heat (steam) requirements are not too high. The heat requirements can become excessive, however, in thin reservoirs where the vertical heat losses above and below the reservoir tend to be high and also in low-permeability carbonates where the reservoir heat capacity per unit volume of contained oil is high.

One potential means for overcoming the problem of heat loss is to use solvents in place of heat to mobilize the oil. Rather than lowering the viscosity of the oil by heating, dilution with a solvent is used instead. In a recent paper<sup>(9)</sup>, it was shown that the recovery mechanism using solvents is very similar to that found with steam. Whereas with steam it is necessary for heat to diffuse into the reservoir by thermal conduction, the process with solvents involves molecular diffusion. The rates at which the processes occur can be described by analogous equations\*.

$$Q = 2\sqrt{2kg\phi\Delta S_oHN} \quad , \text{ m}^3\text{m}^{-1}\text{d}^{-1} \dots\dots\dots (1)$$

where N is a dimensionless number defined for the steam process as

$$N = \int_{T_{\min}}^{T_s} \frac{\alpha\Delta\rho}{\mu} \cdot \frac{dT}{(T - T_R)} \dots\dots\dots (2)$$

In this equation dimensionally consistent units should be used, e.g.

- $\alpha$  = thermal diffusivity,  $\text{m}^2\text{d}^{-1}$
- $\Delta\rho$  =  $\rho_{\text{bit}} - \rho_{\text{steam}}$ ,  $\text{kg m}^{-3}$
- $T$  = temperature, °C
- $\mu$  = bitumen viscosity at T,  $\text{kg m}^{-1}\text{d}^{-1}$
- $T_s$  = steam temperature, °C
- $T_{\min}$  = a temperature slightly above the reservoir temperature  $T_R$

For the solvent process, N is defined as

$$N = \int_{c_{s\min}}^1 \frac{D_s(1 - c_s)\Delta\rho}{\mu} \cdot \frac{dc_s}{c_s} \dots\dots\dots (3)$$

where

- $D_s$  = intrinsic solvent diffusivity,  $\text{m}^2\text{d}^{-1}$
- $\Delta\rho$  =  $\rho_{\text{soln}} - \rho_{\text{solv}}$ ,  $\text{kg m}^{-3}$
- $c_s$  = solvent concentration, vol. fraction
- $\mu$  = solution viscosity,  $\text{kg m}^{-1}\text{d}^{-1}$
- $c_{s\min}$  = a very small solvent concentration

The rate at which the recovery process occurs with a liquid sol-

\*The equations in this paper are dimensionally consistent. Thus, for example, if equation (1) is to yield Q in  $\text{m}^3$  per m of horizontal well per day, then k should be in  $\text{m}^2$ , g in  $\text{m}/\text{d}^2$  and H in m.

**Keywords:** Heavy oil, Vapourized propane, Dew point, Gravity drainage, Heat loss, Mobilization.



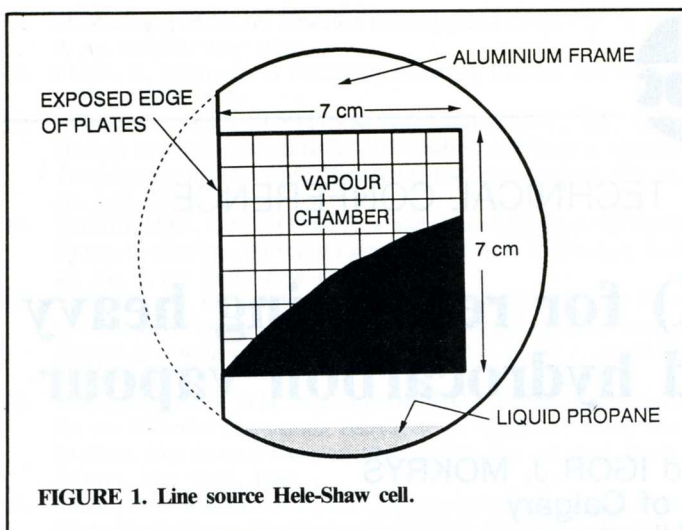


FIGURE 1. Line source Hele-Shaw cell.

vent is disappointingly slow. The reasons for this become clear from a comparison of equations (2) and (3): the molecular diffusivity is smaller than thermal diffusivity and the potential gradient effecting flow is less because of the smaller density difference between the diluted oil and solvent than between the heated oil and steam.

An attractive idea for reducing these obstacles is to use a solvent which is introduced in the vapour form but which, because it is chosen so that it is close to its dew point at reservoir conditions, is highly soluble in the oil. If such a process is carried out at reservoir temperature, the volume originally occupied by the displaced oil is left filled with low-density solvent vapour. Much of this residual solvent can be recovered later by pressure blow-down, and there is no heat loss involved.

Dunn, Nenniger and Rajan<sup>(10)</sup> describe a study of a similar approach in which either carbon dioxide or ethane were injected into a model reservoir at conditions somewhat below their vapour pressures. It is thought that these solvents are generally less effective than propane, which is used here, because, even without added heat, high reservoir pressures are required; operation at temperatures somewhat higher than normal reservoir temperature is not practical because of the low critical points of these solvents (31°C for carbon dioxide and 32°C for ethane).

The preliminary experimental work using a Hele-Shaw cell and propane which is reported later shows that, if this process were performed at the reservoir temperature then, although the rate of oil production would be much higher than that with liquid solvents, it would still be lower than that required for an economic operation. However, it is also shown by the experiments that if the reservoir temperature could be raised to only 40°C to 50°C, then the process would proceed at a faster rate while heat losses would still be vastly lower than those for conventional steam recoveries.

The work reported later develops the idea of using warm vapourized solvents further. The reservoir is warmed by hot water injected simultaneously with propane vapour. This results in a laterally-spreading chamber in which vapour replaces the drained oil.

## Preliminary Experiments

### Development of Apparatus with Line Source Cell

The rate of oil recovery was measured in experiments with a vertical Hele-Shaw cell immersed in an atmosphere of saturated propane. Propane vapour contacted the oil along a vertical edge of the cell and the diluted oil drained from the same exposed edge (Figs. 1 and 2).

As shown in Figure 3, the Hele-Shaw cell was placed in a pressure vessel with two windows, one for photographing the progress of the bitumen drainage, the other for back illumination of the cell. The pressure vessel was immersed in a controlled-temperature oil bath.

The pressure vessel was made of 6061-T6 aluminum alloy and was fitted with windows of 1 in. thick and 4 in. in diameter Tempo

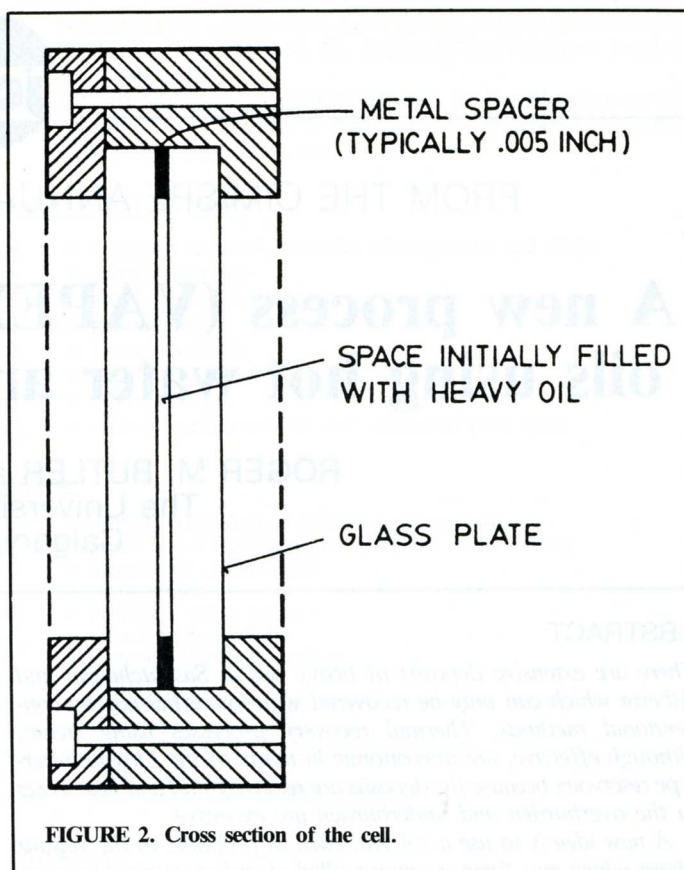


FIGURE 2. Cross section of the cell.

glass. The pressure vessel was tested to 1550 psig with water at room temperature and it can be used for pressures ranging from 0 to 500 psig and temperatures up to 95°C. Operating pressures were between 100 psig and 300 psig; the corresponding saturation temperatures were between 20°C and 70°C. The liquid propane inside the pressure vessel established an equilibrium with its vapour for each bath temperature. The small volume of oil from the Hele-Shaw cell (typically 0.62 ml) then drained to the bottom of the pressure vessel. A section of the cell is shown in Figure 3.

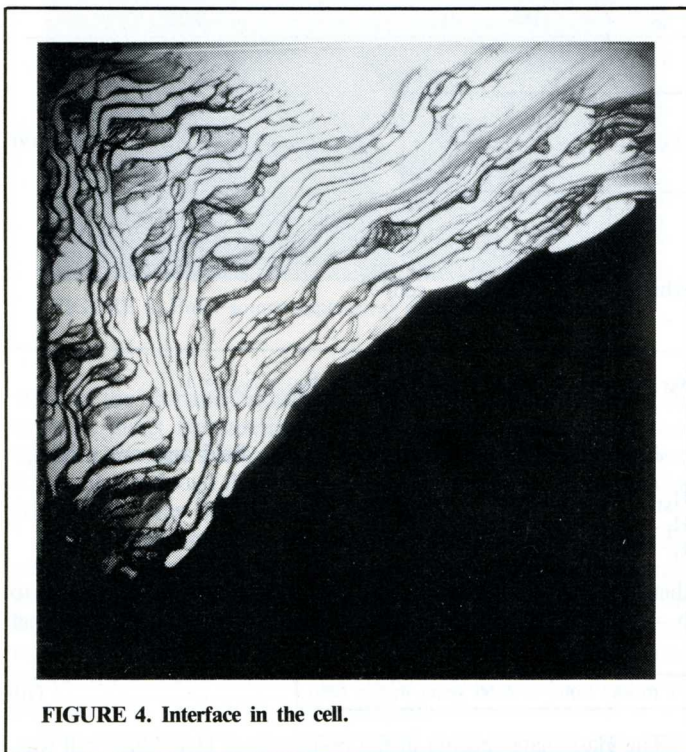
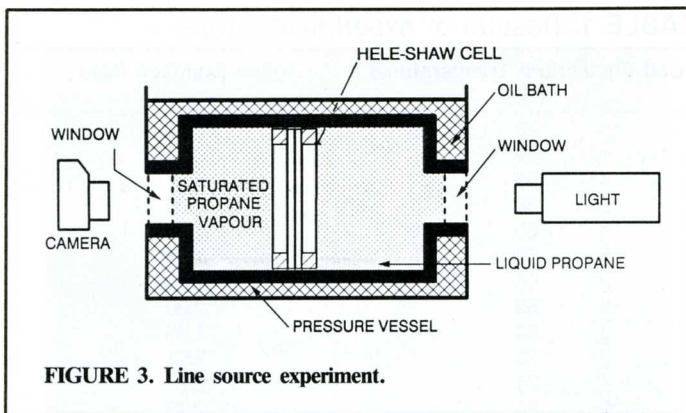
## Results and Discussion of Preliminary Experiments

Figure 4 contains a photograph of a preliminary experiment with Lloydminster crude. This heavy oil contains approximately 12% asphaltenes<sup>(11)</sup>. The photograph shows that the propane vapour mixes readily with the light fractions of the oil, leaving behind some asphaltenes as an immobile precipitate adhering to the glass. It was observed that the drainage occurs in a number of single steps, and that the asphaltenes precipitate out in parallel ribbons, leaving a record of the drainage process on the cells walls. The precipitation of asphaltenes leaves oil which is less viscous and which, therefore, drains more easily.

The precipitation and subsequent behaviour of asphaltene particles should be investigated carefully. Under some conditions, clogging of narrow pore throats of a porous media might occur so as to cause blockages and impairment of the oil flow. This effect should be avoided. One potential way to control the precipitation might be to mix the propane with a non-condensable gas such as nitrogen. This could lower the partial pressure, and therefore, the concentration, of propane below that required for the precipitation. This idea was not followed further in this work because there seemed to be little difficulty caused by the precipitation.

In our experiments with the Hele-Shaw cell a severe blockage and impairment of flow due to asphaltene precipitation has not been observed; the precipitated asphaltenes adhered to the glass walls. However, as reported later, the tendency toward blockage increased at lower temperatures. Danesh *et al.*<sup>(12)</sup> found that miscible displacement of light oil (35.3° API with 2 wt % asphaltenes) with propane did not result in significant precipitation of asphaltenes within the pores. However, if the propane was mixed with crude





oil externally and the mixture was pumped into the reservoir model, then pore blockage due to asphaltene deposition and build-up was observed in their experiments.

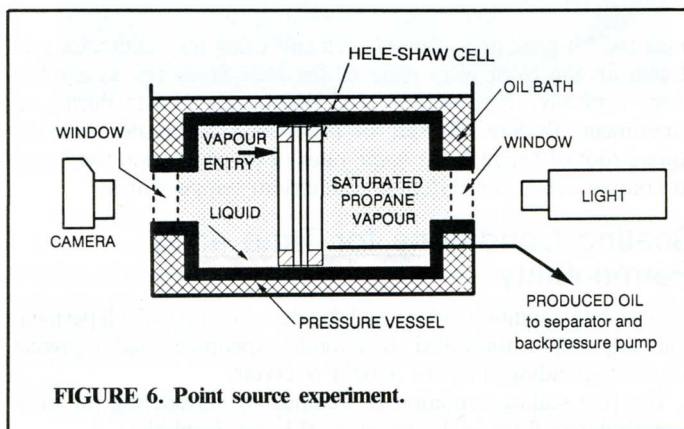
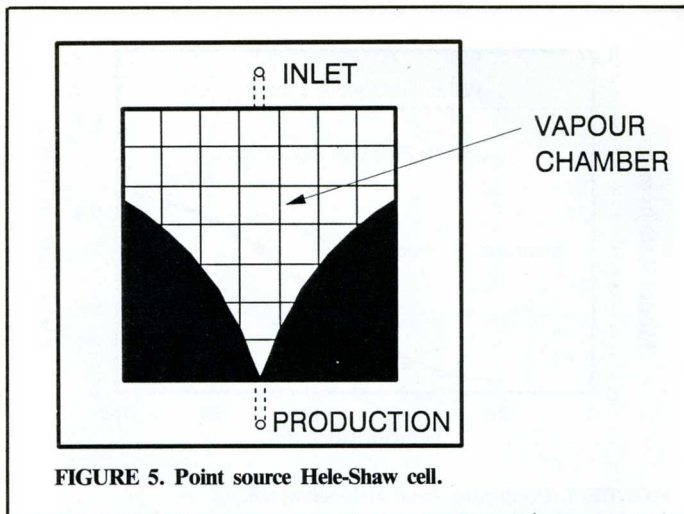
## Improvements of the Experimental Set-up: Point Source Cell - Hele-Shaw Cell

After the initial experiments, several design changes were made to the Hele-Shaw cell and to the apparatus. The line source cell used in the initial work had one vertical edge exposed to the propane and represented one half of a spreading solvent chamber as it would be created in a reservoir located above a horizontal producer. The new Hele-Shaw cell was a point source type with propane injection at a point near the top and with production near the bottom. A schematic drawing of this cell is given in Figure 5. It represents a vertical cross section through a reservoir having two horizontal wells drilled through it, i.e. the injection well near the top and the producer at the bottom. The cell was filled by injecting warm crude oil upward.

After the initial communication has been established, the solvent chamber (which is filled with propane vapour) spreads sideways, displacing the original oil.

## Regulation of Back Pressure and the Rate of Withdrawal

Depending on the equilibrium temperature as determined by the oil bath, the pressure within the Hele-Shaw cell during an experiment was typically between 100 psi and 500 psi. Such a high pressure required a means for regulating the production flow from the



cell to prevent excessive amounts of propane vapour from passing freely through the cell. The production of fluids was controlled by a syringe-type ISCO pump in the production line as shown in Figure 6. The pump was modified internally and several electrical connections were changed so that during an experiment, the pump plunger withdrew total product at a pre-set constant rate.

The effect of the withdrawal rate on the oil production was tested up to a rate of 25 ml/hr. Above a certain value of the withdrawal rate, the oil production was independent of the withdrawal rate (i.e. higher rates only caused more propane to pass unnecessarily through the cell)\*\*. The rate of removal of the products was set a 5 ml/hr and all the experiments in the point source Hele-Shaw cell were carried out with this withdrawal rate. Except at the highest temperatures, this withdrawal rate resulted in some bypass of propane vapour.

A proper technique for setting up the back pressure at the start of the experiment was critical in achieving an early breakthrough along the centreline of the cell. This involved initial pressurization of the pump with nitrogen just below the anticipated equilibrium pressure of the propane. In this way the propane breakthrough in the cell occurred 2 to 3 minutes after the start of the experiment in accordance with the controlled constant rate of withdrawal of 5 ml/hr. During this breakthrough period, propane advanced downward through the cell as a narrow finger which could be seen easily through the window (Fig. 8).

## Evaluation of Production Rates

The oil production rates from the Hele-Shaw cell were evaluated from photographs taken during the course of each experiment. The solvent areas in the photographs correspond to the produced oil and they were determined as a function of time using a planimeter or, in some cases, a digitizing pad. The areas in arbitrary planimeter

\*\*A similar phenomenon is observed in our steam-assisted gravity drainage experiments where excess production of steam results in little additional oil.



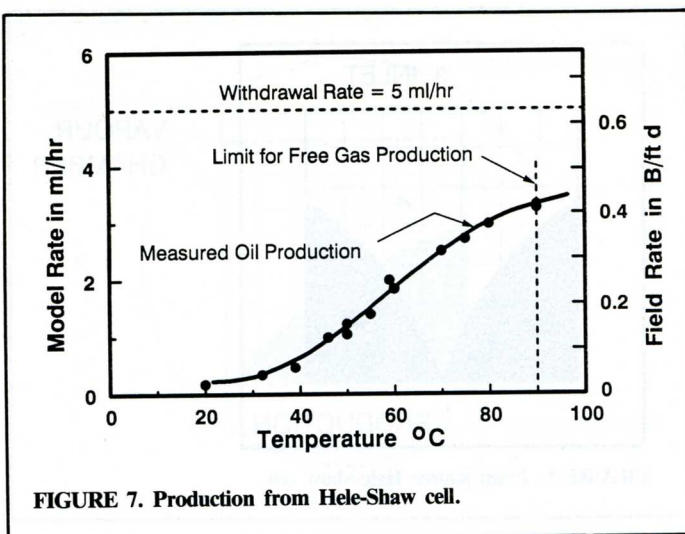


FIGURE 7. Production from Hele-Shaw cell.

units (APU) were then converted to  $\text{cm}^2$  using the centimetre grid drawn on the front glass plate of the Hele-Shaw cell as a reference. Typically, there were 8 to 12 photographs taken during an experiment. Because the rate of production diminishes with the square root of height<sup>(9)</sup>, the *initial* rates of oil production were used to compare runs for different equilibrium temperatures.

## Scaling Conditions for Time and Permeability

Two scaling conditions were used for determining the cell permeability required for the scaled visual model experiments and to predict the corresponding time for a field reservoir.

The first scaling condition is obtained by considering the bitumen drainage flow in the reservoir (List of Symbols).

$$Q_b = \frac{V\phi\Delta S_o}{t} = \frac{k}{\mu} \cdot \frac{dP}{dH} \cdot A \quad (4)$$

Dividing through by the area and replacing the hydrostatic pressure gradient by  $\rho g$  we obtain,

$$\frac{H\phi\Delta S_o}{t} = \frac{k}{\mu} \rho g \quad (5)$$

where  $H$  is the reservoir (or cell) height.

$$\text{Rearranging and using the definition of kinematic viscosity, } \text{kg}t = H\phi\Delta S_o\nu \quad (6)$$

$$\text{or } \left[ \frac{kt}{\phi\Delta S_o H} \right]_M = \left[ \frac{kt}{\phi\Delta S_o H} \right]_F \quad (7)$$

where  $M$  = model and  $F$  = field. The acceleration due to gravity and the kinematic viscosity cancel out in equation (7).

The second scaling condition is obtained from the dimensionless ratio  $Dt/H^2$ , i.e.

$$\left[ \frac{\phi t}{H^2} \right]_M = \left[ \frac{\phi t}{H^2} \right]_F \quad (8)$$

where the diffusivity cancels out and the porosity makes some allowance for the diminished reservoir diffusivity resulting from the volume occupied by the rock pores<sup>†</sup>. Eliminating  $t_F/t_M$  from equations (7) and (8), we obtain

<sup>†</sup>In a porous rock, diffusion occurs over a longer distance and through a smaller cross sectional area than in a simple fluid-filled volume. This effect is inversely proportional to the formation factor used in the theory of formation resistivity.

As a first approximation, this is equal to  $1/\phi^2$ ; because the volume of the pores is only  $\phi$  of the total, the effective diffusivity is  $\phi D$ .

TABLE 1. Results of experimental runs

Cell Equilibrium Temperatures (°C)	Initial Drainage Rate (ml/hr)
20	0.18
32	0.34
39	0.47
46	0.99
50	1.05
50	1.23
55	1.40
59	2.00
60	1.85
70	2.51
75	2.72
80	2.98
90	3.27
90	3.33

$$k_M = k_F \cdot \frac{H_F \phi_M^2 (\Delta S_o)_M}{H_M \phi_F^2 (\Delta S_o)_F} \quad (9)$$

where, for a Hele-Shaw cell<sup>(13)</sup>

$$k_M = \frac{b^2}{12}, \quad \phi_M = 1 \quad \text{and} \quad (\Delta S_o)_M = S_{oi} - S_{or} = 1.$$

Assuming the following values for the field and our model,

$$\begin{aligned} H_M &= .07 \text{ m} & \phi_F &= .35 \\ H_F &= 10 \text{ m} & (\Delta S_o)_F &= .86 \\ k_F &= 1 \text{ darcy} \end{aligned}$$

then the cell permeability,  $k_M$ , is 1356 darcy. This leads to  $b = 5.0 \cdot 10^{-3}$  in. or 127  $\mu\text{m}$ . From equation (8) it also follows that

$$1 \text{ model hour} = 6.66 \text{ years in the field} \quad (10)$$

The glass plate spacing in the point source Hele-Shaw cell was, therefore, set at 5 thousandths of an inch.

## Experimental Results Obtained With the Point Source Hele-Shaw Cell

The objective of this part of the work was to determine the effect of higher propane pressure (and hence temperature) on the production drainage rate from the point source Hele-Shaw cell with a permeability of 1356 darcies (i.e. with plate spacing  $b = .005$  in.). The cell was filled with Tangleflags North heavy oil and immersed in an atmosphere of saturated propane vapour at equilibrium temperatures ranging from 20°C to 90°C. The schematic drawing of the apparatus is given in Figure 6. Photographs taken during the run were evaluated to determine the initial drainage rate for a given cell temperature.

The results are listed in Table 1 and plotted in Figure 7. Table 2 lists the oil density and viscosity as functions of temperature.

As may be seen in Figure 7, the gravity drainage *production rate of oil* from the Hele-Shaw cell increased with temperature up to about 90°C, where the rate began to level off progressively. Also shown in Figure 7 is a horizontal broken line which corresponds to the *total* (vapour plus liquid) withdrawal rate as set by the pump. Thus, as the oil production rate increased from 0.18 ml/hr to 3.33 ml/hr, the propane (liquid plus vapour) leaving with the product decreased from 4.82 ml/hr to 1.67 ml/hr. At the low temperatures, the produced propane volume was almost entirely the excess vapour. At the high temperatures, the produced propane was essentially all dissolved in the produced oil.

The concentration of propane which was dissolved in the oil was thus of the order of 1.7 ml per 3.3 ml of oil, i.e. about 0.5 Bbl/Bbl.





FIGURE 8. Point source experiment at 20°C, 8 minutes.

Because the propane requirements are a critical characteristic of the process, direct measurements of the propane consumption were made in the next series of experiments. However, for the present, it can be concluded that the propane consumption, after allowing for recycle, may not be excessively high.

The measured rates are encouraging, particularly at the high temperatures. Above 60°C, the cell drained in less than one hour and, according to our previous calculations, this would correspond to less than 6.6 years for a reservoir 10 m thick containing 1 darcy sand. In the next version of the process, which is described later, temperatures above ambient have been used and practical production drainage rates have been achieved.

The reproducibility of experimental measurements was satisfactory.

It may be seen from the initial rate measurements presented in Table 1 (e.g. at 50°C, 59/60°C and 90°C) that the rates vary from 2% to 15% for repeat tests at a given temperature. Such variation is to be expected in view of the fact that the whole procedure is very sensitive to the way the pressure vessel is purged prior to the start and to the initial pressure differential established between the backpressure pump and the cell. Both of these factors tend to affect the initial drainage rate. Because drainage rates decrease with the square root of the hydrostatic head of the draining fluid in the cell<sup>(9)</sup>, it is the initial rates that are compared and plotted in Figure 7.

## Experimental Photographs

Two photographs from one of the Hele-Shaw cell leaching experiments are reproduced in Figures 8 and 9.

Each photograph is a close-up view of the glass plates of the vertical Hele-Shaw cell (initially full of Tangleflags North heavy oil) which is illuminated by a light source from the back (Fig. 6). The window area is 7 cm by 7 cm as indicated by a graticule drawn on the glass. The cell rested in an atmosphere of saturated propane vapour above a shallow pool of liquid propane at the bottom of the pressure vessel. The pressure vessel was in turn immersed in a constant temperature oil bath and the whole system was allowed to reach an equilibrium before the start of the experiment. The propane vapour was introduced at the top centre between the glass plates and the mobile oil was drained at the bottom centre. The total rate of drainage was 5 ml/hr, as determined by withdrawal of the ISCO back pressure pump; the plate separation was 0.005 in.

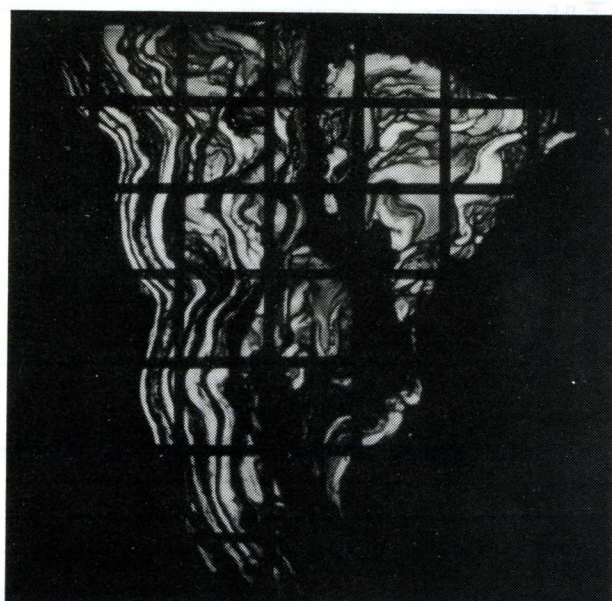


FIGURE 9. Point source experiment at 20°C, 102 minutes.

The photograph in Figure 8 shows clearly the initial breakthrough channel at 8 minutes after the start. One may also notice the formation of incipient side channels and the boundary layer flow alongside the channel walls. During this part of the process, the oil is pushed by the propane. However, the rate of withdrawal is controlled so that a maximum of only 5 ml/hr of propane vapour can bypass.

The photographs showed the formation of a characteristic V-shaped drainage channel. This V-channel is initially narrow (about 45 degrees) but it opens with time (Fig. 9). Each photograph contains a frozen-in record of the drainage history of the whole experiment up to that point. This type of map is only characteristic of a low-temperature propane - bitumen interaction in which some of the lower solubility components (i.e. asphaltenes) precipitate out of the propane solution. The precipitated asphaltenes are then deposited alongside the drainage paths, while the asphaltene-depleted, lower viscosity oil drains to the bottom of the cell. More precipitation was observed in the experiments at lower temperatures. Although the asphaltene precipitates had a tendency to block off the drainage channels partially, no major obstruction to flow was found. This phenomenon may require further investigation.

At 55°C there was less evidence of asphaltene precipitation and no instances of channel blockage were encountered.

At 90°C, the characteristic V-shaped channel was not formed because the rate of product withdrawal (5 ml/hr) was not sufficient to draw propane vapour down to the production well. There was little, if any, asphaltene precipitation in the cell.

In another experiment at 90°C, in which the withdrawal rate was increased to 25 ml/hr, an initial production rate of 10.7 ml/hr of oil was achieved and the usual V-shaped chamber was observed. This demonstrates that it is necessary to inject propane at a rate high enough to force gas solvent to the production well for the gravity mechanism to be effective. An analogous situation is observed in steam-assisted gravity drainage when the rate of product withdrawal is not large enough to draw the steam chamber to the base of the reservoir.

## Initial Rates

The cumulative oil productions for cell temperatures of 20°C, 55°C and 90°C, respectively, are plotted in Figure 10. The initial production rates were obtained from the initially linear portions of the production rate curves at their respective temperatures.

Each of the eight photographs taken during a run was measured with a planimeter to determine the total photograph area and the solvent leached area in arbitrary planimeter units (APU).

The curvatures in the oil production plots are the result of the



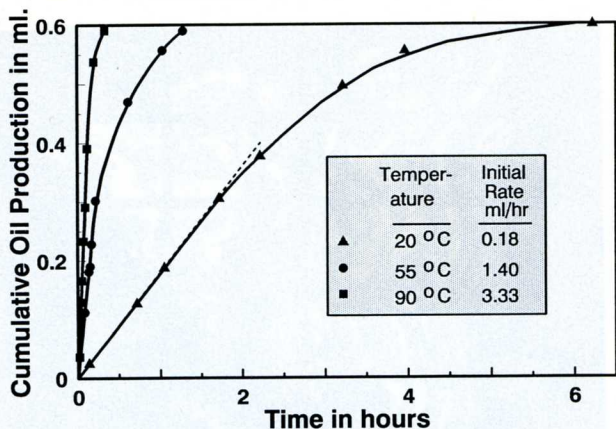


FIGURE 10. Cumulative oil production from point source Hele-Shaw cell.

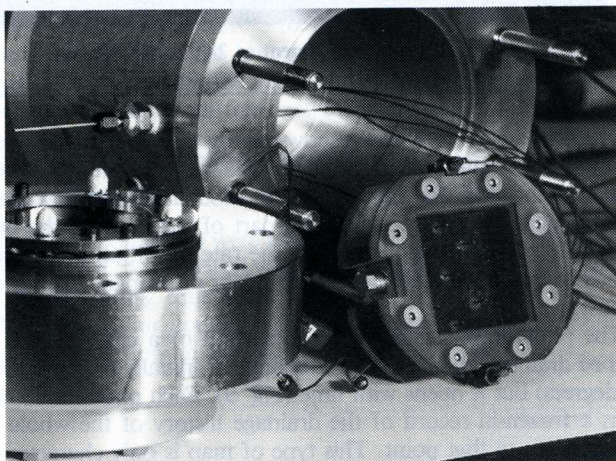


FIGURE 11. Pressure vessel and cell with thermocouples.

diminishing head of oil in the cell. From the authors earlier work, the rate is expected to be proportional to the square root of the head.

## Hot Propane Injection into a Packed Cell — Preliminary Work

The oil drainage experiments obtained with the point source Hele-Shaw cell relied on an outside constant source of heat to establish the equilibrium conditions inside the pressure vessel where the cell was located and drained. The cell was heated to the propane saturation temperature from the outside and each experiment was isothermal. In order to move one step closer to an actual reservoir, it was desirable to design and construct a packed cell and eliminate the external heating bath. In the following experiments, the heat was supplied by means of simultaneous injection of hot water with the propane. This led to the concept of the VAPEX process, which will be discussed later.

## The Design of the Packed Cell

The new packed cell was designed to fit into the existing pressure vessel. It was made of a reinforced phenolic resin to minimize heat transfer by thermal conductivity to or from the walls of the pressure vessel and was equipped with 7 thermocouples located in the back wall. A 7 cm by 7 cm plexiglass window (inert to propane) facilitated viewing of the spreading solvent chamber when required. The inside dimensions of the cells were 7 cm by 7 cm by 2.54 cm. Figure 11 is a photograph of the pressure vessel and of the cell without packing.

The injection port was at the top centre while the producer was located at the bottom centre of the inside of the cell. Two 100 mesh

TABLE 2. Density and viscosity of Tangleflags North heavy oil as a function of temperature

T, °C	$\rho$ , g/cm <sup>3</sup>	$\nu$ , cm <sup>2</sup> /s
19.5	0.9719	10,500
26.5	0.9710	5,800
44.0	0.9656	1,040
54.0	0.9591	510
60.0	0.9552	385
75.0	0.9461	180
90.0	0.9383	88

TABLE 3. Summary of initial hot water-propane runs

Average Conditions		% Recovery of Oil		Initial Oil Rate with Propane
°C	psia	Water	Propane	(g/hr)
32	145	31	88	33.3
34	150	15	85	37.0
36	150	4	84	41.1
47	210	22	83	63.8
43	210	20	93	52.6
35	150	20	85	38.0

TABLE 4. Summary of hot water-propane runs with improved material balance

Average Conditions		% Recovery of Oil		Initial Oil Rate with Propane
°C	psia	Water	Propane	(g/hr)
36	150	21	97	41
45	180	19	89	60
47	200	24	90	62.5
55	250	32	84	63*
44	200	24	86	49*

\*The conditions for these two experiments resulted in a liquid rather than a vapour solvent phase.

wire discs covered the injection and production ports to prevent their accidental blockage by the glass beads.

## Permeability and Time Scaling for the Packed Cell

Using data from reference 14, the following correlation for the permeability of a bed of uniform spheres packed to a porosity of 40% has been developed:

$$k \approx 1150 d^2 \dots\dots\dots (11)$$

where

k is the permeability of the bed in darcies,

and

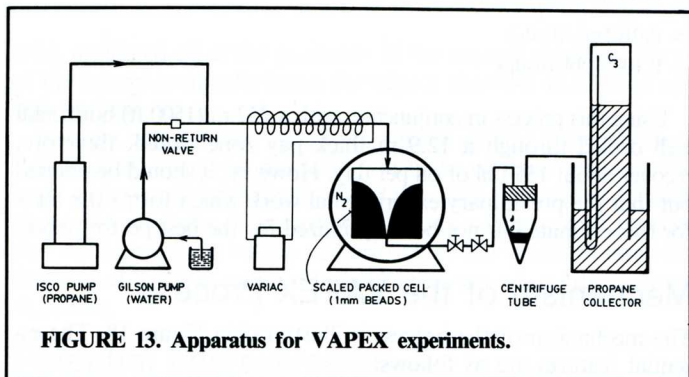
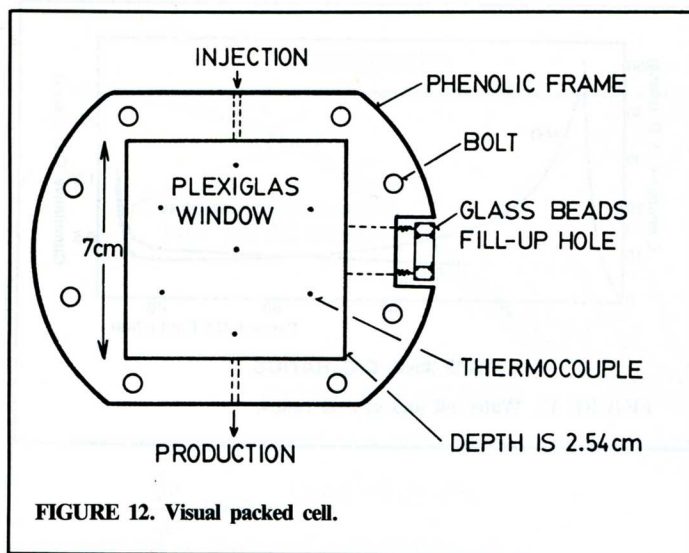
d is the diameter of the packing beds in mm.

The cell was vibro-packed with glass beads of 1 mm diameter to obtain the maximum compaction packing corresponding to a porosity of 39.1%; this corresponds to a permeability of about 1150 darcy. The field permeability chosen was 5 darcy and the average change in oil saturation obtained from experiments in our model was about 0.86. The model and field parameters are summarized below:

$$\begin{aligned} k_M &= 1150 \text{ darcy} & k_F &= 5 \text{ darcy} \\ \phi_M &= 0.391 & \phi_F &= 0.35 \\ (\Delta S_o)_M &= 0.86 & (\Delta S_o)_F &= 0.86 \\ H_M &= 0.07 \text{ m} \end{aligned}$$

Substituting these values into the scaling equation, equation (9), and solving for the reservoir height reveals that this scaled model





represents a vertical cross section through a 12.9 m thick reservoir with a permeability of 5 darcy.

The time scaling may be obtained from equation (8), and for the packed cell

$$1 \text{ model hour} = 4.33 \text{ years in the field} \quad (12)$$

The initial volume of oil in the cell was about 48.7 ml. A freshly packed cell was filled by upward displacement at 40°C with the Tangleflags North heavy oil prior to every experiment.

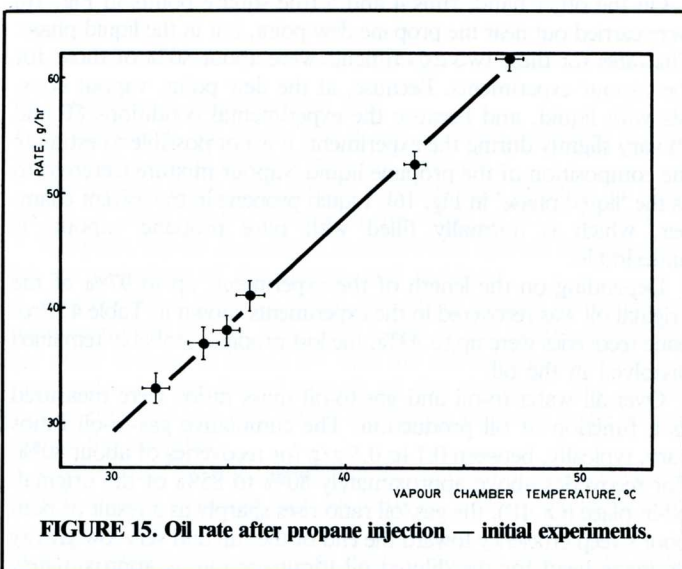
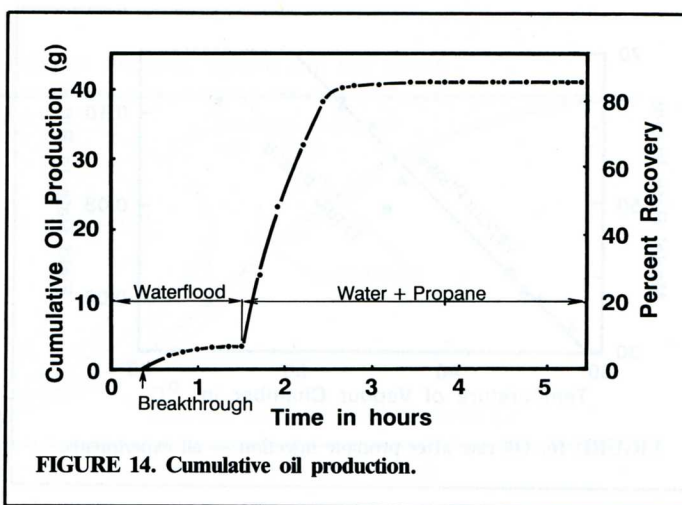
## Heated Water and Propane Injection into the Packed Cell — the VAPEX Process

In these experiments, water and propane were injected at controlled rates using the apparatus shown in Figures 12 and 13. At the start of each experiment, hot water was injected alone and in each experiment, except in run 6 which was at the highest temperature, the oil production rate dropped to almost zero after an hour or so. When this happened, propane vapour injection was started while hot water injection was continued. An example of such behaviour is shown by the recovery data for run 3 which are plotted in Figure 14. The experimental conditions were chosen so that the oil was displaced by propane in the vapour phase at or near its dew point.

The results for the initial runs are summarized in Table 3 and Figure 15.

Figure 15 shows that the oil recovery rate, just after the injection of propane vapour, increases with temperature. We consider that in the case of hot water/propane, the hot water near the bottom of the cell tends to re-vapourize the propane and cause it to recycle. Relatively high production rates are achieved with only a small increase in reservoir temperature. The mechanism and the advantages of the new process will be discussed in a later section.

Propane recoveries during these earlier experiments ranged typically between 85% and 95%. Virtually all of the propane was recovered in the experiments described later which used improved experimental and analytical techniques.



In the work just described the oil and water in the graduated collection tubes were measured by diluting the total sample with toluene containing a demulsifier, centrifuging and finally measuring the separated phases volumetrically. The presence of large amounts of water/oil emulsions greatly obstructed direct determination of water and oil, even after several periods of centrifuging the sample with an added emulsion breaker. This made it difficult to obtain accurate material balances. The problem was overcome by using the Karl-Fischer method to analyze for emulsified water; the next experiments utilized this improved technique and accurate material balances were obtained.

## Oil Determined by Karl-Fischer Analysis

Following the experiments summarized in Table 3 an additional six runs were carried out with improved analyses and control. They are summarized in Table 4. The water in produced samples (and therefore by difference the oil) was measured using an automated Karl-Fischer titrator††.

Accurate water, oil and propane balances were obtained for the experiments. As an example, in the fourth run, the total oil determined from analyses of the contents of 21 sample tubes and of the cell was 49.23 g; this total is in good agreement with the weight of oil put into the cell. This was 49.19 g.

As can be seen from Table 4 and Figure 16, runs 1, 3 and 4 agree well with the straight-line relationship plotted in Figure 16 for the earlier experiments.

††KF Processor 658, Metrohm Ltd. CH-9100 Herisau, Switzerland, using a one-component reagent HYDRANAL - Composite 5 (No. 34805, made by Fiedel-de Haen AG - D-3016 Seelze 1). The titration is based on the fact that sulphur dioxide can be oxidized by iodine in the presence of water, i.e.  $I_2 + SO_2 + 2 H_2O \rightarrow 2 HI + H_2SO_4$ .



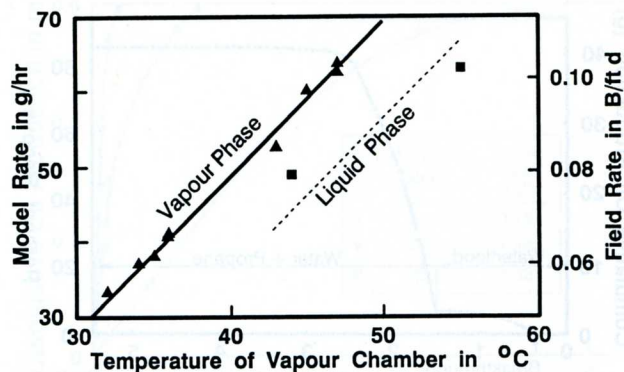


FIGURE 16. Oil rate after propane injection — all experiments.

On the other hand, runs 4 and 5 (the square points in Fig. 16) were carried out near the propane dew point, but in the liquid phase. The rates for these two experiments were about 80% of those for the vapour experiments. Because, at the dew point, vapour coexists with liquid, and because the experimental conditions (T and P) vary slightly during the experiment, it is not possible to estimate the composition of the propane liquid/vapour mixture (referred to as the 'liquid phase' in Fig. 16). Liquid propane in the solvent chamber, which is normally filled with pure propane vapour, is undesirable.

Depending on the length of the experiment, up to 97% of the original oil was recovered in the experiments shown in Table 4. Propane recoveries were up to 99%, the lost propane probably remained dissolved in the oil.

Over-all water-to-oil and gas-to-oil mass ratios were measured as a function of oil production. The cumulative gas-to-oil ratios vary, typically, between 0.1 to 0.5 g/g for recoveries of about 80%. For recoveries above approximately 80% to 85% of the original-oil-in-place (OOIP), the gas/oil ratio rises sharply as a result of both poor sweep efficiency toward the end of the run and very low gravity drainage head for the diluted oil (drainage rate is approximately proportional to the square root of the head). For this reason, most experiments were stopped at about 85% to 90% recovery of oil.

The gas-to-oil ratio and water-to-oil ratio for the experiment shown in Figure 14 (i.e. run 2) are plotted in Figure 17. In this experiment the total water injected was 8 times the volume of oil produced for a recovery of 80% of OOIP. The ratio of the cumulative injected propane to the cumulative produced oil was about 0.4 for the same recovery; 99% of the injected propane was recovered.

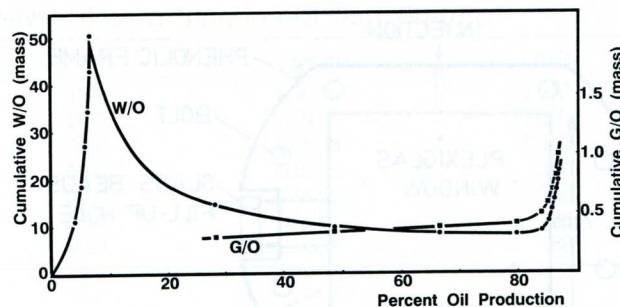
## Scaling of Production Rates for the Packed Cell

The initial production rates in Tables 3 and 4 can be scaled to predict the field performance of the new process. The fourth run in Table 3 will be used as an example. It was carried out at 47°C and the initial production rate of 63.8 g/hr was obtained in the packed cell 7 cm high and 2.54 cm deep. Assuming the reservoir height of 12.9 m developed previously and using the time scaling factor defined by equation (12) with  $\rho_{\text{oil}} = 1 \text{ g/cm}^3$ , the model production per unit depth of cell is:

$$63.8 \frac{\text{cm}^3_{\text{M}}}{\text{hr}_{\text{M}}} \cdot \frac{1}{2.54 \text{ cm}_{\text{M}}} = 25.12 \frac{\text{cm}^2_{\text{M}}}{\text{hr}_{\text{M}}} = 0.002512 \frac{\text{m}^2_{\text{M}}}{\text{hr}_{\text{M}}}$$

Substituting for one model hour from equation (12) and considering that  $0.07 \text{ m}_{\text{M}}$  is equivalent to  $12.9 \text{ m}_{\text{F}}$ , the equivalent field production per 1 m of well is:

$$0.002512 \frac{\text{m}^2_{\text{M}}}{4.33 \text{ yr}_{\text{F}}} \cdot \left[ \frac{12.9}{0.07} \right]^2 \frac{\text{m}^2_{\text{F}}}{\text{m}^2_{\text{M}}} = 19.70 \frac{\text{m}^2_{\text{F}}}{\text{yr}_{\text{F}}}$$



W/O AND G/O RATIOS

FIGURE 17. Water/oil and gas/oil ratios.

$$= 0.054 \frac{\text{m}^2_{\text{F}}}{\text{d}_{\text{F}}}$$

or field production per foot of well

$$\begin{aligned} &= 0.0165 \text{ m}_{\text{F}}^3 / (\text{ft} \cdot \text{d}_{\text{F}}) \\ &= 0.1035 \text{ bbl} / (\text{ft} \cdot \text{d}_{\text{F}}) \end{aligned}$$

Using this process in conjunction with a 457 m (1500 ft) horizontal well drilled through a 12.9 m thick pay zone would, therefore, recover about 155 bbl of oil per day. However, it should be pointed out that the preliminary experimental work which forms the basis for this estimate has not been optimized for the best performance.

## Mechanism of the VAPEX Process

The mechanism of the process is illustrated in Figure 18. The essential features are as follows:

Following hot water/propane injection into the reservoir, an initially vertical solvent vapour chamber is formed between the injector and the producer. Within this chamber the solvent is recycled by evaporation from the diluted draining oil which is heated by the hot water. The warm propane vapour rises countercurrently to the draining water and increases its temperature as it comes in contact with hotter water near the top of the reservoir. It then moves to the far reaches of the chamber where it dissolves in the cold undiluted reservoir oil.

The vapour chamber spreads laterally. The oil-solvent interface becomes stabilized by gravity and acquires its characteristic S-shape for each half of the chamber. The drainage is controlled by molecular diffusion of solvent vapour into the bitumen through the irregular, deviating pores of the matrix.

The function of the hot water is twofold: it heats the reservoir and lowers the oil viscosity in the process; this heating also releases propane vapour from warm draining oil for re-use at the top of the vapour chamber.

Although heat is used in the process, the quantity is small compared to that required for a comparable steam process; because the temperatures are low, the heat losses are low and this should allow economic operations in much thinner reservoirs.

The lateral spread of the vapour chamber is made possible by the combination of continuous transport of heat to the perimeter of the chamber through the mechanism of solvent evaporation and condensation with the continuous removal of diluted oil by gravity drainage. The function of the solvent (e.g. propane) is, therefore, also twofold: it dilutes the oil in the far reaches of the solvent chamber and it distributes the heat laterally away from the plane of injector and producer. As a result, a large expanse of reservoir can be drained from a pair of injection and production wells.

The process of boiling off some of the solvent from the diluted draining oil sets up a small pressure gradient in the vapour phase which is sufficient to drive the re-vaporized solvent toward the

†It consists of a very thin band (referred to as the convection or diffusion boundary layer) in which the diluted oil is transported by gravity drainage<sup>(9)</sup>.



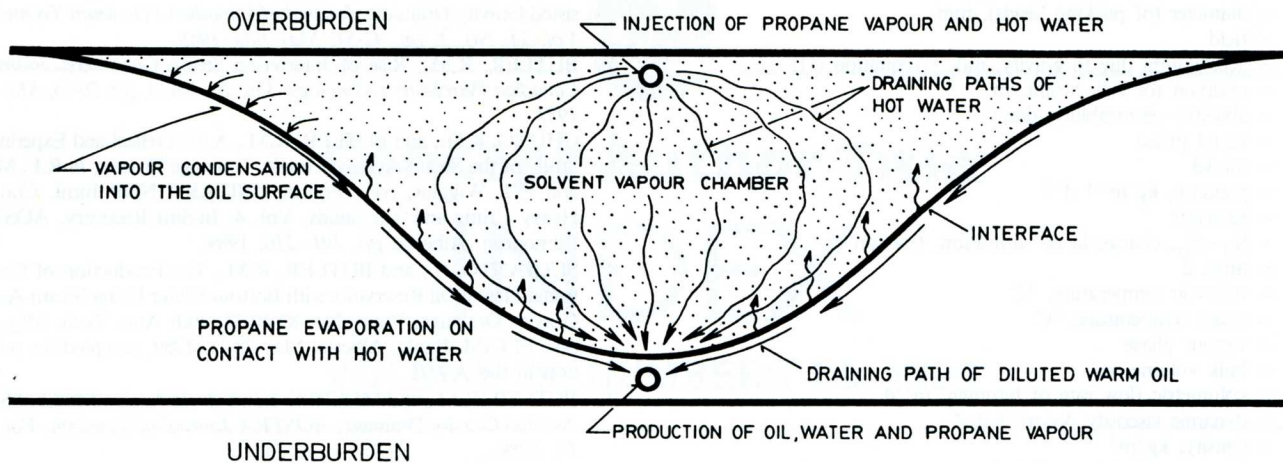


FIGURE 18. Mechanism of VAPEX Process.

cold, undiluted oil at the perimeter of the vapour chamber. Some of the solvent eventually leaves the vapour chamber as solution gas and free gas.

In order to maximize the solvent vapour contact with the reservoir, and therefore the rate with which the oil can be recovered, both wells should be drilled horizontally, with the injector located above the producer. The authors envisage a commercial process that would involve a battery of horizontal wells spaced at intervals determined by the extent of the lateral spread of the solvent chambers.

## Potential Improvements

It was shown above that drainage rates in the order of 0.1 bbl/(d-ft) could be anticipated in the field. Although somewhat lower than rates for steam-assisted gravity drainage, this value seems high enough for the process to be economically viable under some circumstances. It should be appreciated that, up until now, there has been no attempt at optimization in our experiments. There are opportunities. For example, higher temperatures than 47°C should give higher rates and more attractive extrapolations to field conditions. It is also possible that improved techniques of operation may be developed. For example, pressure cycling could be beneficial.

Another possibility is to optimize the process by locating the injection well lower in the reservoir — an attractive configuration might be to place the injection well at about one-third of the height of the reservoir. This would produce a more favourable temperature distribution with only the lower part of the reservoir heated and would allow more internal refluxing of the extraction vapour. There would be a larger hold-up of propane within the reservoir but a lower concentration in the produced fluids and a lower requirement for propane recycling.

This approach, because it would facilitate the establishment of communication (very hot water, even steam could be used for the initial communication phase), would extend the application of the technique to more viscous oils such as the tars in Grosmont, Cold Lake and Athabasca. The application to the Grosmont carbonate reservoir could be particularly attractive because, even though its permeability may be high, its low porosity tends to make the heat requirements for conventional thermal processes excessive. With the propane/hot water technique, the high heat capacity of this low-porosity reservoir per unit quantity of contained oil is of lesser importance. There is also some indication that the Grosmont deposit may be oil-wet rather than water-wet. If this is the case, then it appears that, if asphaltenes are precipitated, they will be more likely to remain adhering to the rock at the point of precipitation rather than be swept along by the draining fluid to the production well.

## Conclusions

A new vapour extraction process (the VAPEX Process) that allows economic production of oil from heavy oil reservoirs is proposed.

Its fundamental characteristics are:

1. A mixture of hot water and a low boiling vapourized solvent such as propane is injected into the reservoir.
2. The injected fluids must contain sufficient heat to warm the reservoir to a temperature typically in the range of 40°C to 70°C.
3. A solvent vapour chamber is formed which spreads laterally from the vertical plane of the injector and producer.
4. As the diluted bitumen drains by gravity toward the producer, it interacts with the hot water and a part of the dissolved propane (or other solvent) is boiled off into the solvent chamber where it propagates further lateral growth of the chamber. The solvent vapour thus acts as a heat carrier and causes warming at the boundary of the chamber.
5. Experimental evidence shows that the injection of propane vapour with hot water results in high oil recovery. This is far higher than could be obtained with hot water alone.
6. The propane requirements in the experiments were of the order of 0.5 kg or less, per kg of oil recovered, for an oil recovery of 80%. Nearly all of the injected propane was recovered with the oil. It is anticipated that, with the development of the process, operation with a much lower recycle of propane will be achieved.
7. The advantages of this new process are:
  - the solvent is inexpensive and can be recovered and recycled;
  - there are much smaller heat losses involved in the process than with conventional steaming; and
  - the process is suited for thin reservoirs as well as thicker ones.
8. Another area where the new process may have potential advantages is in the recovery of heavy oils and bitumen from low porosity but good permeability reservoirs such as the Grosmont Karsts in Alberta.
9. A variation of the process which involves the injection of steam with some propane near the bottom of the reservoir may, in some cases, be more attractive.

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## LIST OF SYMBOLS

- A = flow face area, m<sup>2</sup>  
 APU = arbitrary planimeter units, dimensionless



b	= Hele-Shaw cell plate spacing, $\mu\text{m}$
d	= diameter (of packing beads), mm
F	= field
g	= acceleration due to gravity, $\text{md}^{-2}$ [equation (1)]
H	= reservoir (or cell) height, m
k	= absolute permeability, darcy
l	= liquid phase
M	= model
P	= pressure, $\text{kg m}^{-1} \text{d}^{-2}$
R	= reservoir
$\Delta S_o$	= $S_{oi} - S_{or}$ , change in oil saturation, fraction
t	= time, d
$T_R$	= reservoir temperature, $^{\circ}\text{C}$
$T_S$	= steam temperature, $^{\circ}\text{C}$
v	= vapour phase
V	= bulk volume, $\text{m}^3$
$Q_b$	= volumetric flow rate of bitumen, $\text{m}^3/\text{d}$
$\mu$	= dynamic viscosity, $\text{kg m}^{-1} \text{d}^{-1}$
$\rho$	= density, $\text{kg}/\text{m}^3$
$\nu$	= kinematic viscosity, $\text{m}^2 \text{d}^{-1}$
$\phi$	= fractional porosity

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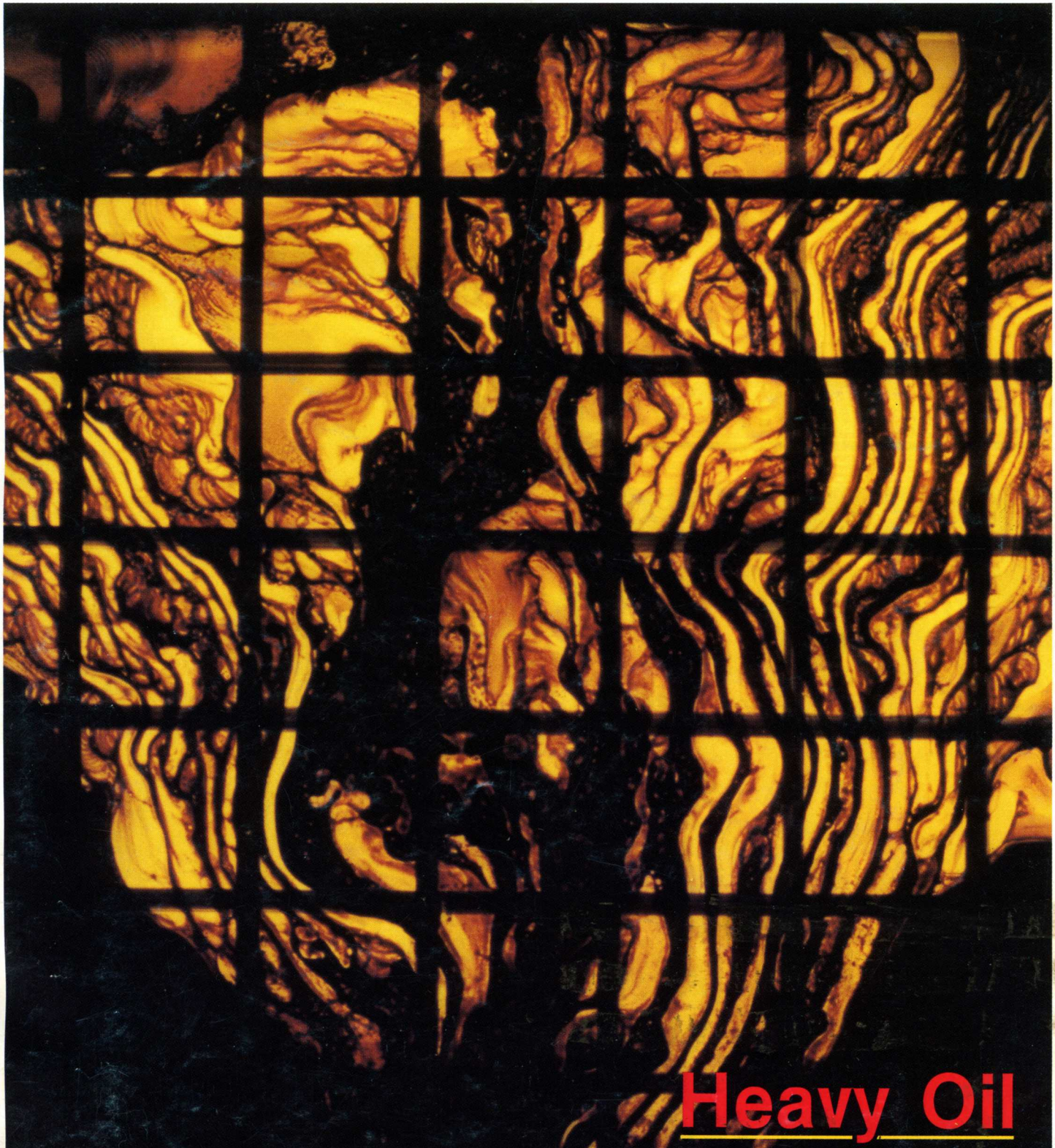




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