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I. Introduction

Research and development efforts in support of the Tar Sands program well completions and stimulation subactivity and new and novel concepts task have been initiated. The objectives of the well completion and stimulation efforts are to carry out research and development in areas with significant potential for long-range tar sand extraction development as well as provide interaction and support of the near-term tar sand field experiments. Evaluation testing of packers and computational analysis of well bore insulation for tar sands steam recovery injection wells have been investigated this quarter. Production well completions for the tar sand steam drive experiment have been examined, and a program to measure downhole steam quality in the experiment is under development. Initial examination of the application of the DOE downhole steam generator program to tar sand reservoirs has commenced.

The examination of new and novel concepts for extraction of tar sands has been initiated. An overburden replacement technique was evaluated both computationally and in a laboratory scale experiment. Analyses of both microwave heating and in situ hydrogenation are being initiated.

II. Well Completion

A. High Temperature Packers

A test program for evaluation of high-temperature packers has been established for examination of performance under conditions encountered in thermal recovery from deep reservoirs. The thermodynamic parameters are more severe than those expected in current tar sands projects; however the data can be related to conditions of interest in tar sands recovery through application of analysis developed for the study of enhanced aging.

The rates of chemical reactions are functions of temperature. The mechanisms accountable for the failure of packers are related to chemical bonding. An example of a failure mechanism for an elastomeric seal element in a packer is an increase in the number of bonds between molecules which results in the embrittlement of the material. Relationships between the development of failure processes with time and temperature are given through the Arrhenius relationship for the quantity of a reaction product Q ,

$$Q = At \exp(-\Delta E/RT) , \quad (1)$$

where ΔE is the activation energy, R is the gas constant, T is the temperature, and t is the time. Using the Arrhenius equation to determine the thermodynamic conditions T_1, T_2 which will produce the same quantity of reaction product in times t_1, t_2

$$\ln \left(\frac{t_1}{t_2} \right) = \frac{\Delta E}{R} \left(\frac{1}{T_1} - \frac{1}{T_2} \right) . \quad (2)$$

An example of the time-temperature relation for an oxidizable elastomeric material used in packer seal elements is given in Figure 1.

The high-temperature packers which have been evaluated to date were manufactured by Brown Oil Tools, Baker Packer, Haliburton, and Guiberson. The Brown and Guiberson packers were commercial units, the Baker and Haliburton packers were modified versions of commercial units. The packer performance obtained in a test at 640°F is given in Table 1. The equivalent of survival for a five-day test at the elevated conditions is equivalent to several years under the conditions of the Tar Sand Steam Drive field test (TS-1S). The existing commercial high-temperature packers which failed during the simulation test would probably not fail in the tar sand experiment for periods of anticipated operation.

B. Insulated Injection String

Insulated injection string is not currently utilized in steam recovery operation at depths less than 1000 ft. The tar sands steam drive field test is at a depth for which insulation is not used in existing heavy oil steam drives. The low flow rates which are anticipated in the tar sands experiment increase the attractiveness of applying insulation to the injection string. Analysis of the steam flow in the string has been carried out for two injection conditions. The injection conditions used in the analysis were those of the initial injectivity test carried out by LETC.

	<u>Temperature</u>	<u>Flow Rate</u>
Case A:	430°F	263 lb _m /hr
Case B:	460°F	526 lb _m /hr

FIGURE 1.

TABLE 1
High Temperature Packer Test

Test Conditions: Temperature = 650°F
Pressure = 2100 psi

<u>PACKER</u>	<u>TEST NO.</u>	<u>TEST TIME</u>	<u>RESULTS</u>
Brown Emjay	GE-1	2 days	No seal at packer.
	GE-2	5 days	Held with small steam leak, difficult to pull.
Halliburton CT	GE-3	2 hours	No seal, set in tension.
	GE-4	0 hours	Seal failed at 1000 psi, set in tension.
	GE-5	24 hours	Seal failed, set in compression.
Guiberson	GE-6	2 days	Seal failed.
	GE-7	23 hours	Seal failed.
Baker HB-1 (with advanced seal)	GE-8	1/2 hour	Seal leak.
	GE-9	4 days	Packer seal held.
	GE-10	0 hours	Injection string joint failure.

In both cases, the surface steam quality was 80%. Calculations were carried out using the Sandia wellbore heat loss code,⁽¹⁾ which provides a one-dimensional description of the steam flow. The governing equations are

$$\frac{dT}{dz} = \frac{\frac{q}{GA} - \left(\frac{Cf}{8A}\right)G^2v^2 + A^*\left(\frac{q}{G^2v} - \frac{Cfv}{8A}\right)}{v \frac{\partial p}{\partial T} - \frac{\partial h}{\partial T} + A^*\left(\frac{\partial v}{\partial T} + \frac{1}{G^2} \frac{\partial p}{\partial T}\right)} \quad (3)$$

$$\frac{dx}{dz} = \frac{\left(\frac{Cf}{8A}\right)G^2v^2 - g - B^*\left(\frac{q}{GA} - g\right)}{B^* \frac{\partial h}{\partial x} + (B^* - 1)G^2v \frac{\partial v}{\partial x}} \quad (4)$$

where

$$A^* = \frac{\left(\frac{\partial h}{\partial x}\right)}{\left(\frac{\partial v}{\partial x}\right)} \quad (5)$$

and

$$B^* = \frac{v \frac{\partial p}{\partial T} + G^2v \frac{\partial v}{\partial T}}{\frac{\partial h}{\partial T} + G^2v \frac{\partial v}{\partial T}}$$

where

- A = cross-sectional area of injection tube
- C = circumference, inside surface of injection tube
- f = friction factor for pipe flow
- G = mass velocity
- g = acceleration of gravity
- h = steam enthalpy
- p = pressure
- q = heat transfer rate per unit length of injection tube

(1) C. E. Hickox, "Wellbore Heat Loss for Steam Injection Into Deep Reservoirs", SAND 79-1298, October 1979.

T = temperature
v = specific volume
z = axial coordinate
x = steam quality

The simultaneous solution of the above equations subject to the initial conditions $T(0) = T_0$ and $x(0) = x^0$ allows the determination of the steam temperature and quality as functions of position along the injection tubing.

It was found that for case A and no insulation (bare wall) that the steam quality had dropped to zero 400 ft. from the surface. At the higher injection rate of case B the steam quality is only 12% at 580 ft. Clearly there is a need for improvement. One possibility is the use of an insulated injection string. If one inch of calcium silicate insulation is added to the outer surface of the injection string, the steam quality is increased to 47% for case A and to 62% for case B. Another possibility is to use the commercial product developed by General Electric, Thermocase III. The gain in steam quality above that for calcium silicate is not great; $x = 59\%$ for case A and $x = 68\%$ for case B. If steam quality of 50% or greater is to be maintained at depth, it will be necessary to insulate the injection string if normal oilfield practice is to be followed in the injection process (e.g., the annulus is not heated).

C. Review of Well Completion for TS-1S

A review of the experimental plan of LETC TS-1S by Completion Technology Company indicated some concerns for the practical completion of the tests. The rather high pressures that are to be used are in excess of the lithostatic pressure. This excess can induce extensive fracturing, especially if substantial hot water drive occurs. Then live steam can have access to the production wells. The production wells, with type K casing, are not designed to withstand large temperature differentials (could be as high as $\Delta T = 275^\circ\text{F}$). The lack of sizing information of the sands resulting from production makes it difficult to estimate the effectiveness of the sand filters (screens). Reasonable assumptions indicate that sand control will be a problem. The hydraulic pumps cannot handle sand and will be quickly damaged if large quantities of sand are present. The rather large viscosity, even at elevated temperatures (of the order of 100 cp), would place severe strain upon the production pumps.

D. Measurement of Downhole Steam Quality

The measurement of downhole steam quality in the tar sand experiment TS-1S is being pursued through application of a downhole sampler, designed to obtain a known volume of steam at the sand face. Measurement of the mass of the fluid trapped by the sampler is sufficient to provide a set of two equations for the mass of the vapor phase and liquid phase water at the downhole location. The sampler is designed to require a minimum of surface control and appears to be compatible with existing well head configurations when applied with a well head lubricator.

E. Downhole Steam Generator

The downhole steam generator program carried out by DOE under the DEEP STEAM project appears to have significant possible application to the tar sand program. The depth of most tar sand reservoirs is not as great as those for which the program is directed. However, heat loss in tar sand steam drive is expected to have a more detrimental effect on the quality delivered to the sand face than in a heavy oil reservoir at the same depth. The greater loss in steam quality is due to lower injectivity of the tar sands. The ability of some of the generator designs under consideration to mobilize the oil at large distances ahead of the condensation front could have significant economic implications for recovery of the highly viscous bitumens. The possibility of overcoming environmental problems with downhole steam production is also attractive. Computational investigations and laboratory scale experiments to evaluate the application of this technology to tar sands production are being initiated.

III. New and Novel Concepts

A. Overburden Replacement

A technique proposed for recovery of shallow tar sands involves strip mining of the overburden followed by construction of a pool of water over a hydrocarbon-bearing formation. A schematic diagram of such a recovery operation is shown in Figure 2. The water within the pool has a greater density than the oil within the formation, constituting the conditions for a classical Rayleigh-Taylor instability. The unstable condition is relaxed by reversing the positions so that the lighter liquid is on top, having been displaced by the liquid with greater density. The hydrocarbons, which have moved to the surface, can

FIGURE 2. SCHEMATIC REPRESENTATION OF OVERBURDEN REPLACEMENT (FLIP-FLOP) METHOD FOR THE RECOVERY OF BITUMEN FROM SHALLOW TAR SANDS.

be easily collected without the need for additional mining. Modifications to enhance the recovery process include using hot water, addition of surfactants, and drilling of penetrating wells. The recovery of tar sands by this process of removal of overburden and replacement with a water pool has been analyzed from the view of the properties of the fluids involved and the reaction of these fluids to the applied recovery forces. In addition, bench scale experiments were conducted to test some of the recovery procedures.

The statement of Darcy's Law, applicable to most oil recovery processes is

$$\vec{v}_m = -\hat{e}_h \frac{K_h}{\mu} (\nabla P) \cdot \hat{e}_h - \frac{K_v}{\mu} \left[(\nabla P) \cdot \hat{e}_v + \rho_o g \right] \hat{e}_v, \quad (6)$$

where $k_{h(v)}$ is the horizontal (vertical) permeability of the reservoir, P is the pressure, $\hat{e}_{h(v)}$ is a unit vector in the horizontal (vertical) direction, and v_m is the porous flow velocity. The driving force for the overburden replacement method is the bouyant force instead of a pressure gradient, for this process

$$\vec{v}_m = - \frac{K_v}{\mu} (\rho_w - \rho_o) g \hat{e}_v. \quad (7)$$

Thus, the driving force for most enhanced oil recovery techniques acts on the reservoir fluids through the horizontal permeability; however, the overburden replacement mining processes act through the vertical permeability. The stratigraphic nature of the sedimentary formations which comprise oil reservoirs results in a horizontal permeability much larger (often by a factor of 5) than the vertical permeability.

The rate of production, based on v_m , is

$$\Omega = \frac{a K_v}{\mu} (\rho_o - \rho_w) g. \quad (8)$$

Evaluating the predicted recovery for a large recovery project where

$$K_v = 2 \text{ Darcies}$$

$$\mu = 130 \text{ Ns/m}^2$$

$$\rho_o = 975.19 \text{ kg/m}^3$$

$$\rho_w = 10^3 \text{ kg/m}^3$$

$$g = 9.8 \text{ m/s}^2$$

$$\alpha = 1 \text{ square mile}$$

the predicted recovery is 4.95 BOPD.

The effect of temperature on the recovery rate in an overburden replacement operation can be determined from equation (7). An increase in temperature can affect the density difference between the crude oil and water, and can affect the oil viscosity. The change in density of bitumen with temperature is not significantly greater than that of water. The major effect of heat addition on the recovery rate is therefore the reduction in viscosity of the oil.

The rate of production from an overburden replacement operation can be increased by heating the water pool. If the pool is heated to 130°F, the predicted production rate increases from 3-5 BOPD to 780-1300 BOPD.

If the pool were heated to 130°F, the heat loss from air convection over the pool surface would be a major problem. The energy loss would be equivalent to 7000 BOPD from the one square mile pool. The pool heat loss without insulative measures is thus greater than the production from the project. The cost of insulation of the surface would be expected to be prohibitive in addition to interfering with the attractive simplicity of the recovery technique.

A series of laboratory-scale recovery experiments was carried out to test the results of the computational analysis of the overburden replacement recovery method. A core sample consisting of an unconsolidated sand matrix (2 Darc permeability) and 12.5° API crude oil was utilized in the experiments. The cores used in the test had very small quantities of connate water. Samples were also prepared which consisted of the same crude oil without the presence of a reservoir matrix. Testing of the recovery of the 12.5° API oil by locating the water pool above the oil without the effect of the reservoir matrix resulted in rapid recovery of 99% of the oil within six hours.

Measurement of oil produced in the laboratory experiments with reservoir matrix averaged over several weeks was $1.5 \times 10^{-8} \text{ m}^3$ of oil per day from vessels with .114 m diameter surfaces at the oil/water interface. The recovery predicted from the same theoretical analysis as used to evaluate the large scale field operation was $1.3 \times 10^{-8} \text{ m}^3$ of oil per day. The small scale experimental test agrees with the mathematically predicted production rate for an overburden replacement operation.

B. Microwave Heating

Another concept for enhanced oil recovery is by the microwave heating of the bitumen to lower its viscosity and hence increase mobility. A systems analysis will be undertaken in the second quarter to establish the feasibility and economic requirements of this approach. Some preliminary experiments reported in the literature indicate that L band (915 MHz) does not penetrate deep enough into the formation to be useful. However, lower R.F. heating (about 30 MHz) may be more promising.

C. In Situ Hydrogenation

One possible enhanced oil recovery concept involves hydrogenation of the resources prior to and during recovery to improve physical and chemical properties. A literature search disclosed a number of undeveloped patents and little information on laboratory assessment. A sample of Kern River crude was analyzed. The core sample contained 7.5 weight % pentane soluble oil, and another 19% by weight was removed upon ashing. The residue from the ashing will be used for assessment of catalysis from the formation.

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