Final Report

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**SCALED-PHYSICAL-MODEL STUDIES
OF THE STEAM-DRIVE PROCESS**

Final Report

✓ T. M. Doscher, *Principal Investigator*
Department of Petroleum Engineering
University of Southern California
Los Angeles, California 90007

950 7194

Harold Lechtenberg, *Technical Project Officer*
San Francisco Operations Office
Fossil Energy Division
1333 Broadway
Oakland, California 94612

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I. PREFACE

This is the final report of a successful three year program sponsored by the United States Department of Energy, San Francisco Operations Office, to study scaled physical models for furthering the understanding of the steam drive and its potential for the recovery of crude oil.

Very special words of thanks and appreciation are due Mr. Harold Lechtenberg, the project officer in Oakland, who expended the effort to insure that the project was able to continue to an appropriate conclusion.

In order to conserve on resources, this report has been limited to a summary statement of the findings and conclusions of the overall project with separate chapters devoted to an account of specific tasks which came to fruition during the latter part of the project. They have been condensed as they would be for publication in the technical literature. Anyone interested in greater details of the experimental and quasi-theoretical methodology that was employed can secure the information by requesting the doctoral dissertation of the participants (see section II) from the University of Southern California, or by contacting the principal investigator, Dr. Todd M. Doscher. (After September 1, 1982 at 8948 Wonderland Park Avenue, Los Angeles, CA 90046.)

II. INTRODUCTION

More steam than water is now injected into California reservoirs and production from steam injection operations exceeds the production from water floods. The recovery efficiency in steam drive operations, in general, appears to be higher than that of any other recovery process, exceeding 50 to 60% of the oil in place.

The principal goal of this project, initiated in October 1977 and concluded this past September, was to gain an understanding of the influence of controllable, operating practices and of reservoir parameters on the steam drive. A field project can only be conducted once, and the exigencies of running a profitable project frequently make it difficult to study a variety of ways for optimizing its performance. With scaled physical models, it is of course possible to repeat the exploitation of the prototype in as many ways as can be conceived.

The use of scaled physical models for studying physical processes is an established discipline in the physical sciences and engineering. Its use depends upon a knowledge of the interrelationships of independent and dependent parameters, but not on the use of the explicit formulation of the relationships. It is not a universally applicable technique because it is not always possible to simultaneously scale all the relationships between the independent and dependent variables. The steam drive, because the chief phenomena of fluid flow and heat flow obey the same laws of diffusion, can be physically scaled.

The principal deficiency of scaled physical models in representing a steam drive operation is in modelling the fine details of the lithology of the reservoir. This is an inherent deficiency in any kind of reservoir simulation. However, the steam drive does not appear to be very sensitive to pore size distribution, capillary pressure and relative permeability when the absolute permeability is above, say, one darcy. Only the absolute value of permeability and porosity appear to be important. Gross heterogeneities, if not too prevalent, can be introduced into the models.

The validity of the results of the scaled physical models is evidenced by the correspondence of the results with those reported in field operations. Hence, it does appear to be valid for studying ways for predicting and optimizing steam drive operations in high permeability sands. When conclusions are drawn from physical models of prototypes which are significantly different from those for which some confirming field data is available, there is bound to be some concern for their validity; this is particularly true for the conclusions that have been

drawn on the steam drive in very high and very low gravity crudes, and in thin reservoirs.

Before enumerating the major conclusions of the study, it is to be noted that Dr. S. Rhee, now with Aminoil, Dr. W. Huang, now with Union Oil, Dr. O. Omoregie, now with Chevron, and Dr. F. Ghassemi, now with Conoco, contributed to the conception and implementation of the studies that were undertaken under this project. Each developed his doctoral dissertation from the original effort they contributed.

III. SUMMARY OF THE RESULTS OF PROJECT STUDIES

A. THE GRAVITATIONAL INSTABILITY OF A STEAM DRIVE

Steam does not frontally displace viscous crude oil. This conclusion may be readily reached by a simple calculation of the pressure gradient required to displace a high saturation of viscous oil. The scaled physical model studies have proven that the flow of steam is not diffuse under these conditions, but stratified. No matter where steam initially enters the formation at the well bore, it will migrate upwards until a physical barrier to its continued rise is encountered. This phenomenon cannot be avoided because of the much lower density of the steam compared to that of the reservoir liquids.

Figure 1 is a conceptual sketch of rising steam and falling oil; the maximum velocity of the rate of steam rise can be readily calculated from this configuration as being equal to:

$$v_{\max.} = \frac{k_o g \rho_o}{\phi \mu_o \Delta S_o}$$

For a medium having a permeability (k_o) to oil of one darcy, and a porosity (ϕ) of 0.3, experiencing a desaturation (ΔS_o) of 0.5 of an oil which has a viscosity of 10 cps at steam temperature, the maximum rate of rise of the steam finger is between 1 and 2 feet per day. The rate of advance of the steam finger will of course be lower than this idealized rate because condensation and a pressure drop will occur within the steam finger; neither of which is accounted for in the preceding idealized equation.

B. THE ROLES OF OIL VISCOSITY AND STEAM TEMPERATURE (PRESSURE) ON THE PRODUCTION OF CRUDE OIL WHEN THE STEAM FLOW IS STRATIFIED.

After the steam has risen to encounter a barrier, its subsequent flow to the producing well will be over and across the top of the oil column. The pressure gradient in the steam zone is relatively small; most of the energy being consumed at the producing well and to a lesser extent at the injector. The volumetric ratio of the flow of oil to the flow of steam will be an inverse function of the respective viscosity ratio at steam temperature. However, the ratio of the mass flow rates will be a function of the inverse ratio of the kinematic viscosities at steam temperature:

$$S/O \propto \left(\frac{\mu_o / \rho_s}{\mu_o / \rho_o} \right)_{T_s}$$

This ratio is a unique function for each crude oil, and does increase with temperature although both kinematic viscosities decrease with temperature. The kinematic viscosity

of the crude ultimately decreasing faster than that of steam.

A very important finding of this study is the fact that for a crude with a moderate viscosity, e.g., Kern River field crude, the ratio increases to a sufficiently high value at temperatures as low as 212°F to permit an economic oil steam ratio to be reached at that temperature. On the other hand, very viscous crudes and bitumens may require temperatures above 500°F for the above ratios to reach a level that will permit an economic oil steam ratio to be attainable.

C. THE EXTENSION OF THE STEAM DRIVE TO TARS AND BITUMENS

Some of the earliest attempts to develop the steam drive were aimed at reservoirs containing very viscous petroleum substances; the so-called tar sands. However, to date, virtually all of the economically successful steam drive operations have been conducted in reservoirs containing crude oils which have yielded some primary production; crudes which have some mobility at original reservoir conditions. Unfortunately, prevailing economic factors have in large measure prevented efforts to define economic feasibility of steam drives in tar sands from coming to fruition.

Actually, the oil steam ratio is correlated against the product of the ratio of kinematic viscosities (see chapter above) multiplied by the quality of the steam entering the reservoir. Delivering high temperature steam, required for the bitumens and tar sands, at a high quality is beset with problems because of the heat losses in the distributing systems and down hole tubulars combined with the relatively low latent heat of high pressure steam. Further, in order to maintain the low kinematic viscosity of oil as the producing well is approached, a significant back pressure on that well may have to be maintained. This will of course exacerbate the problems of producing such hot fluids and vapors.

The results of the scaled physical model studies indicate that it will indeed be difficult to economically produce these very viscous materials by a straight forward application of the steam drive. Extrapolation of the scaled physical models results, obtained to date, indicate that an oil steam ratio much greater than 0.10 will be difficult to achieve. An oil steam ratio of 0.10 will result in a ratio of energy produced to energy expended of 1.3, viz., only 23% of the bitumen produced can be used for product sales. Even before refining losses are taken into account, the profitability of such an operation appears to be remote. (Such bitumens will have to be produced by more efficient processes, viz., steam stimulation, or by the addition of synergistic agents to the steam drive.)

D. THE OCCURRENCE OF THE OPTIMUM STEAM INJECTION RATE

The oil-steam ratio, in addition to being a function of the steam quality and the ratio of kinematic viscosities, is also a function of the rate of steam injection. It has been possible to empirically determine an optimum flow rate for the prototypes studied in this work and they have been found to be in agreement with optimum rates that have been identified in field operations; in the range of 100 to 150 BWD of 60 to 70% quality steam.

The existence of an optimum is related to the occurrence of the overlay of the steam and its breakthrough to the producing well. At very low rates, the steam channel cannot be established. At very high rates, the steam channel is established relatively quickly, but after breakthrough the utilization of the steam drops very rapidly since the release of heat is determined primarily by the thermal properties of the reservoir.

Even at the optimum rate of injection, the maximum thermal efficiency is reached at the time of steam breakthrough and decreases thereafter. However, the rate of steam injection cannot be lowered so as to eliminate the production of some uncondensed steam. There is a conflict between maximizing the thermal efficiency and the maximum oil-steam ratio. Some uncondensed steam must continue to be produced, and an appropriate pressure level must be maintained within the reservoir in order to insure that the required ratio of kinematic viscosities is maintained throughout the reservoir. The optimum rate is that rate which gives the maximum oil-steam ratio.

E. EMULSIFICATION AND OIL PRODUCTIVITY

Figure 2 is a conceptualization of overlay of steam across the top of the oil column. Steam condensate floods the interface, and oils which are less dense than water will be flushed upwards by the condensate descending through the oil column (the inverse of the events leading to the rise of the steam zone, Figure 1.) Since the interface is inundated by the steam condensate, the conditions there are rife for the formation of oil in water emulsions. The effective viscosity of the emulsified crude will be lowered towards that of water; it does not appear that rigid film forming substances are active at elevated temperatures. In the scaled model studies, as in the field, the oil produced in steam drive operations is always emulsified to some extent. This phenomenon is believed to be an intrinsic and very favorable one in the implementation of steam drives.

It may therefore be anticipated that if the crude oil and condensate interact to promote emulsification, the oil steam ratio will respond favorably as will the overall recovery efficiency. Such an effect has already been observed and reported in pilot operations in the Athabasca Bituminous Sands. These observations can be extrapolated to the search for additives to the injected steam for the specific purpose of enhancing emulsification of oil at the steam oil interface.

F. THE ROLE OF RESERVOIR THICKNESS

In steam drive operations which are dominated by an overlay of the steam, significant heat losses to the base rock do not occur until the steam interface approaches the base rock. Hence, if the injection rate and spacing are the same, the steam ratio should be independent of reservoir thickness until oil depletion has extended far enough to bring the oil steam interface within a certain distance from the base rock. Scaled model studies have shown that a 25 foot thick prototype gives virtually the same oil steam ratio as does a 70 foot prototype. Although experiments with thinner reservoirs were not completed, quasi-theoretical extrapolation of the model results suggest that a 10 to 15 thick prototype of a representative San Joaquin heavy oil reservoir will perform virtually as well as a thicker reservoir.

Thus, in contradiction to the significant increase in oil steam ratio as a function of thickness that is predicted by steam driven models that are based on frontal displacement; the physical model studies indicate that the oil steam ratio will be more or less constant as the thickness increases above, say 15 feet, as long as the steam quality and the ratio of the kinematic viscosities is held constant. However, as the depleted zone thickens, the potential for gravity segregation of the steam vapor and its entrained water and condensate increases. The top of the oil column may become so innundated with water that the oil interface is occluded from the steam vapor. This would result in a significant deterioration of the efficiency of the steam drive. Thus, the oil steam ratio can be expected to decrease for the same fractional recovery of oil as reservoir thickness continues to increase. Field results, limited as they are, do confirm these conclusions.

Although these conclusions point to a relatively small thickness as being the optimum one with respect to oil-steam ratio, it is obvious that when such factors as the capital cost per barrel of produced oil is also taken into account the economic optimum spacing will not coincide with that which results in the maximum oil-steam ratio.

G. CYCLIC INJECTION OF STEAM IN A STEAM DRIVE

Model studies were conducted on the cyclic (diurnal) injection of steam drive, as would occur if a stand-alone solar steam generator was used. The results indicated that if the hourly rate was doubled and maintained for only half a day, the recovery and the oil steam ratio would be more or less the same as in the case of the reference operation. Even more important, however, the model studies revealed that if the optimum rate was maintained for only half the day, the oil steam ratio was not seriously affected although the time required to achieve the same recovery was somewhat more than twice that of the reference continuous injection operation.

This result indicated that the cyclic injection of steam, resulting in a corresponding cyclic pressurization of the reservoir (and, of course, a lower average pressure) compensated in large part for the increased heat losses to the cap rock as a result of the lower rate of heat injection. If this result is extrapolated to conventional steam drives, it could be concluded that the oil steam ratio of such conventional steam drives rather than continued continuous injection.

H. HIGH GRAVITY CRUDES

In model experiments in which prototype high gravity crudes were employed rather than the low gravity crudes, which are the conventional target for steam drive operations, the mechanism of the displacement shifted dramatically. Now, the steam flow was diffuse and the displacement piston-like in character. High steam injection rates resulted in very high oil steam ratios. Even when using prototypes containing residual (to water flood)

saturations of high gravity crudes, the displacement was so efficient that favorable oil steam ratios, 0.15 to 0.25, could be attained. It is important when considering these results, to appreciate that a favorable oil steam ratio merely refers to the fact that significantly more energy is produced than is consumed in the process: 2 to 3.5 times as much for the cited ratios (corresponding to 50% to 70% of the production being available for sale). However, the ultimate economics of the drive will also depend upon the capital investment required. For many high gravity crudes in the United States, reservoirs are relatively thin and therefore large patterns are required to keep the well costs per barrel at a reasonable level. Large spacing will in turn require large injection rates. This requirement will undoubtedly pose a limitation on the number of high gravity crude oil reservoirs that could be a target for the steam drive.

I. THE PARTIAL SUBSTITUTION OF INERT GAS FOR STEAM

Steam provides two functions in a steam drive: a heat transmitting fluid and a driving fluid. Optimization of both functions rarely coincide. In most steam drive operations, an excess of heat is injected into the reservoir in order to provide a sufficient drive to displace the heated crude. Model experiments have demonstrated that an inert gas can be substituted for some of the steam to maintain the required displacement of the oil while not diminishing the amount of oil that can be heated and mobilized. Although the technological feasibility of such a substitution is apparent, it is not certain that it is economically justified because of the cost of inert gas in comparison to that of steam. It is anticipated that 0.5 to 1 million standard cubic feet of inert gas would be required to replace the function of 100 barrels of steam per day. This means that the affordable cost of the delivered, compressed gas would have to be in the range of \$0.25 to \$0.50/MSCF. Hence, the "inert gas" will have to be air, which is not precluded, or it

will need to be shown that the use of an inert gas can be further optimized in its ability to substitute for steam.

Although no model experiments have been conducted with soluble gases, such as carbon dioxide, the matter of its use has been studied by project personnel in the light of the conclusions drawn from the project. Soluble gases have been proposed for use in conjunction with steam because it has been reasoned that additional viscosity reduction can be achieved by the solution of the soluble gases in crude oil. The analyses that have been conducted indicate that the optimum conditions for the efficient use of steam and for the potentially effective use of soluble gases are diametrically opposed. The solubility of gasses in crude oil increase with high pressure and low temperature. Steam is most efficiently used at low pressure and high temperature. Therefore it does not appear that these two materials would be in any simple way synergistic. There is probably much more optimization to be achieved in controlling and adjusting the independent controllable parameters in a steam drive than can be achieved by the addition of soluble gases.

IV. THE ANTICIPATED EFFECT OF DIURNAL INJECTION ON STEAM EFFICIENCY

A. INTRODUCTION

In recent years as much steam as water has been injected in California oil fields, and the production is somewhat greater from steam injection operations than from water floods. The steam drive in California has become a mature and standard production practice.

As more and more information is reported, it is becoming apparent that the steam drive is perhaps the most efficient of all recovery techniques in terms of volumetric recovery efficiency. It appears that only in some natural water-driven reservoirs in east Texas and south Louisiana will the recovery efficiency reach the 50% to 60% range which many steam drives are reported to be attaining.

The steam drive is characterized, after steam breaks through to the producing well, by a slow but steady decrease in the ratio of oil produced to steam injected until the ratio falls below a economic value. The major cost for steam generation is the cost of the fuel used for steam generation. The cost of the fuel is directly related and comparable to the value of the crude; frequently it is the produced crude itself which is used to fuel the steam generator. The use of any fuel which is cheaper to use than the produced crude would permit a higher ultimate recovery to be achieved before the economic limiting oil-steam ratio is reached. Moreover, with cheaper steam the steam drive might be extended to the recovery of high gravity crudes after water flooding, and low gravity tar sands¹. The anticipated oil-steam ratios for both of these targets appear to be only marginally economic at this time as long as the produced petroleum is to be used as the source of fuel for steam generation. For example, at an oil-steam ratio of 0.1 only 23% of the recovered petroleum is available for product sales. Even before refinery losses are taken into account it is apparent that the profitability of such a venture would be remote. The only justification for such a recovery operation would be as a means for producing liquid fuels and not as a means for making available new energy supplies, per se.

In keeping with these conclusions, some attention has been given to use of coal and lumber mill wastes for steam generation, but feasibility studies indicate that transportation, handling and other costs, particularly in California, are so great that these intrinsically cheaper fuels are more expensive to employ than crude oil is at this time.

The suggestion has been made that solar energy be used to develop steam for such projects. Certainly, the economic advantage of solar energy for other than hot water heating is yet to be proven in the market place. Although solar energy is an inexhaustible resource, and it is not necessary to pay for the privilege of capturing it, the capital, operating, and maintenance costs, still to be quantified, are very high.

However, of serious concern to our nation is the matter of providing a significant fraction of our needs for liquid fuels in the future. Although at this time the relationship between supply and demand has become ameliorated due to the interplay of numerous political and economic factors, an ultimate deficiency in adequate domestic supplies of liquid fuels is still to be anticipated². It is therefore not unreasonable to believe that massive solar power systems may yet be indicated for the future recovery of crude oil in our country.

Solar power is of course cyclic in nature. Table 1 indicates the relative availability of sunlight for power generation in the San Joaquin Valley. Useable power is thus available for only a third of the day, and there is a 25% variation between the peak of summer and the dead of winter. It was the purpose of this study to investigate the performance of steam drives when a diurnal, cyclic supply of steam is employed.

B. EXPERIMENTAL

Most of the model work has been confined to continuous steam injection operations. In order to conduct cyclic drive operations, it was necessary to revise the injection equipment.

For the model/prototype combination that was used, one half day corresponded to 1.4 seconds. It was obviously impossible to open and shut the inlet valve manually to maintain a consistent cyclic flow of steam. Further, opening and closing a well head valve caused the upstream generating system to fail in providing a constant delivery of controlled quality steam to the model. It was thus necessary to use a three-way solenoid-actuated valve so that during the "off-cycle" the steam was vented through a dummy model. In this way, the steam generator operated continuously against a constant back pressure, and during the "on-cycle" the steam was turned into the model reservoir.

Also, most models in the past were quarter five-spots equipped with two injectors and one producer. Maintaining an approximately equal distribution of steam into the two injectors during continuous operations was manageable but it proved extremely difficult to maintain such equal distribution in an on-off mode. Therefore, the scaling and the models were redesigned as one eighth five spots with one injection well and one producer. Other than these changes, the experimental procedures were identical to those already described.

The prototype is a 6-acre (2.4 ha) five spot in a 70 foot (21.3 m) thick sand with a porosity of 35% and an initial oil saturation of 80%. The prototype oil is a viscous crude having a viscosity of 40,000 cps. (40 Pa.s) at 80°F (26.7°C), original reservoir temperature, and of 5.4 cps. (0.0054 Pa.s) at the temperature and pressure of the injected steam, 460°F (238°C) and 427 psia (61.9 kPa). The prototype steam quality is 64% at the sand face.

Three experiments were conducted. In the reference run, A, the steam injection rate was maintained at a constant level of 28 barrels (4.45 m³) of water converted to steam per hour, or 670 BWD (107 m³WD). In run B, the hourly rate was increased to 56 barrels (8.90 m³) but only for a half day; the daily rate was still 670 barrels (107 m³) of converted water. Finally, in run C the hourly rate was held to 28 barrels (4.45 m³) but for only twelve hours a day to give a total daily rate of only 335 barrels (53.3 m³).

C. RESULTS

Each run was initiated by the continuous injection of steam at the reference rate of 670 BWD (107 m³WD) until steam breakthrough occurred. At this time, a tongue of steam extended from the injection well to the production well across the top of the model. This was done so that the long term efficiency of a diurnal, cyclic steam drive could be compared with continuous injection without the possible confusion which would occur by the introduction of differences due to the time required for the initial breakthrough of steam to the producing well. The previous work had already established the fact that in the absence of steam stimulation of the producing wells, the amount of heavy oil produced before steam breakthrough is a very minor part of the total produced by steam drive.

When runs A and B, in which the same total amount of steam is injected daily, are compared; it is apparent that oil production and oil-steam ratios (Figures 3 and 4) show a difference which indicates that continuous injection is superior to diurnal injection in early years. However, after several years the efficiency of the diurnal system approaches that of the continuous steam injection operation. This suggests that in the early years of the diurnal operation, the steam zone, when it is not very substantial, may be cyclically collapsing or not even being maintained in the vicinity of the production well. However, since the time for the injection of the same amount of heat is the same for both runs, the overall heat loss to the cap rock will also be of the same order of magnitude for each run although the distribution of heat across the reservoir may be somewhat different. Eventually, as the heat becomes distributed throughout the length of the reservoir, the distribution of the steam zone in the case of diurnal injection approaches that for the case of continuous injection, and the oil production of the former accordingly approaches that for continuous injection.

When the results of diurnal injection, Experiment C, in which the total daily steam injection is half (hourly rate the same) of that in the reference experiment, A, it is apparent that the production rate is slightly less than half that achieved by continuous injection, see Figure 3. Correspondingly, the oil-steam ratio is only slightly less than that attained by continuous injection, Figure 4.

It had been expected that because the time elapsed for the injection of the same amount of heat is doubled, resulting in the heat losses to the cap rock being increased by the order of 40%, the oil-steam ratio would be seriously affected by the switch to diurnal injection. One or more compensating factors must have come into play to prevent the oil-steam ratio from falling more than it did. Although these factors cannot be unequivocally identified, the most likely one is the fact that the average steam pressure in the reservoir is lower than in the case of continuous injection. As a result of the lower average pressure, the temperature is somewhat lowered, diminishing heat losses due to a lower temperature differential, per se. Further, because the average steam pressure is lowered the kinematic viscosity and the steam vapor velocity are both increased which further the ability of the steam to drag or displace the oil to the producing well^{2,3}. A second factor is that more heat is accumulated in the oil-bearing sand beneath the stratified steam zone, and a greater thickness of oil may be mobilized by the stratified steam flow.

Alternating pressurization and blowdown in steam drive operations has been proposed for increasing the oil-steam ratio to be achieved in the exploitation of Peace River Tar Sands⁵. The concept of cyclic pressurization in steam drive operations may therefore be a general technique for optimizing oil-steam ratios.

D. CONCLUSIONS

A comparison of diurnal injection of steam with continuous steam injection for the prototype used in this physically scaled model work indicates that the ultimate requirements of steam for the production of a given amount of crude oil would not be significantly affected by the use of a stand-alone solar steam generator. However, in order to maintain the same rate of oil recovery, it would be necessary for the solar generator to provide a sustained rate which is two to three times that used in conventional, continuous injection. Although the same amount of oil would be produced at overall lower diurnal rates, the time required would be proportionately increased. As a result, the economics of the operation would be penalized by higher present value capital costs per barrel of production.

The study has also indicated that in any steam drive operation there may be merit in considering cyclic injection of steam into injection wells to optimize the oil-steam ratio.

V. THE EFFECT OF OIL VISCOSITY AND RESERVOIR THICKNESS ON THE STEAM DRIVE

A. INTRODUCTION

Physical scaled models of the steam drive^{1,2,3} have reproduced many of the features of field operations. One of the most pronounced features of the steam drive is the overlay of the steam above the oil column and its subsequent stratified flow to the producing well.

This is in contrast to the frontal displacement that was assumed in early analytical models. The effect of various reservoir and operational parameters therefore may have different effects than those originally deduced based on frontal displacement.

Three very important parameters which have been used to assess the feasibility of steam drive operations are the rate of injection of steam and its quality, the viscosity of the crude oil, and the thickness of the reservoir. The analytical model that has been most frequently used⁴ and its modification^{5,6} do not attribute any effect of the crude oil viscosity on the efficiency of the steam drive. The growth of the steam zone and the corresponding depletion of oil are based exclusively on the way in which heat is distributed within the reservoir. The quality of the steam and its injection rate are both shown to be important with the resulting oil-steam ratio monotonically increasing with each. On the other hand, field and model studies have indicated there is an optimum rate of steam injection to attain a maximum oil-steam ratio. The analytical models predict that the efficiency of the steam drive process, as measured by the oil-steam ratio, will vary directly with a function of reservoir thickness whereas field evidence suggests that the thickness may not have the pronounced effect that is predicted.^{7,8}

It was the purpose of this work to attempt to elucidate the role of oil viscosity and reservoir thickness in steam drive operations in which gravity segregation of the steam and its stratified flow dominate the process.

B. STEAM DRIVE ANALYSIS BASED ON STRATIFIED STEAM FLOW

Steam initially enters a viscous oil reservoir through a depleted or wet interval, a fracture, or a fluidized interval. If the initial entry is not at the top of the oil section, then the steam rapidly migrates upwards because of the strong gravitational gradients imposed by the marked difference in density between the steam and the reservoir fluids. The rate of upwards migration depends on the vertical permeability and the viscosity of

the crude oil at steam temperature, viz., the concurrent drainage rate of the heated crude.

After the steam reaches an impermeable barrier that prevents further upwards migration, continued injection of steam appears to result in a vertically expanding steam zone; the production of crude oil occurring as a result of attrition by the steam flowing above and across the oil column. Newman⁹ has presented an analysis of such a process based on observations made in Kern River field steam drive operations. The occurrence of stratified steam flow is taken into account in the scaled model experiments by the inclusion of the ratio of the kinematic viscosity of the steam to that of the crude at steam temperature¹.

Given this conceptualization of the steam drive process, Figure 5, it is apparent that the transfer of heat to the oil column is occurring at a moving boundary, and then the heated oil at the boundary is swept or dragged to the producing well. However, the process probably becomes still more complex after the oil-depleted zone attains a significant thickness. Gravity segregation of the steam and its condensate appears to become a factor with the latter tending to inundate the surface of the oil column. If the density of the water is less than that of the crude the oil may be occluded from the influence of the steam and the recovery of crude may come to a halt. If the water is denser than the oil, it will penetrate into the oil column causing oil to rise to the interface, see Figure 5, and the steam will be driving a mixture of oil and water. Should an oil in water emulsion form under the influence of the condensing steam drive, the efficiency might be expected to increase. Indeed, there is significant evidence that in a mature steam drive, emulsification^{10,11} is an important recovery mechanism in the steam drive.

A differential equation for the transfer of heat to a moving boundary as postulated above is available in the literature¹². The integration of the differential equation results in the following:

$$Q_{oc} = (\lambda \Delta T / 2v) [2v(t/\alpha)^{0.5} \text{ierfc}(v/2)(t/\alpha)^{0.5} + 2 \text{erf}(v/2)(t/\alpha)^{0.5}] \quad (1)$$

where v is the velocity of the decending interface between the steam and the oil column, t is the time since the arrival of the steam at a particular element of the interfacial area, and Q_{oc} is the cumulative amount of heat transferred to the oil column per unit interfacial area.

In addition to this utilization of injected heat, some of the heat is also stored in the oil-depleted, steam zone, Q_{sz} and some is lost to the cap rock, Q_{cr} :

$$Q_s = v \rho c t \Delta T \quad (2)$$

$$Q_{cr} = \rho c \Delta T \int_0^{\infty} \text{erfc} \frac{z}{2\sqrt{\alpha t}} dz \quad (3)$$

By defining the following dimensionless quantities:

$$t_D = v^2 \cdot t / 4\alpha, \quad (4)$$

$$A_D = v \cdot \rho \cdot c \cdot \Delta T \cdot A / \dot{Q}_i, \text{ and} \quad (5)$$

$$Q_D = \dot{Q}_i \cdot t \cdot v / (4\lambda \cdot \Delta T); \quad (6)$$

the total heat stored in the reservoir and the boundary rocks, as a dimensionless expression, is as follows:

$$Q_{TD} = Q_{szD} + Q_{crD} + Q_{ocD} \quad (7)$$

$$Q_{TD} = t_D + (t_D/\pi)^{0.5} + (t_D/4)^{0.5} \text{ierfc}(t_D)^{0.5} + 0.25 \text{erf}(t_D)^{0.5} \quad (8)$$

An examination of the preceding equation will show that the heat usage in raising the temperature of the depleted zone will be constant (if v is constant) whereas the rate at which heat is added to both the cap rock and the oil column decrease with time. (the heat stored beneath the moving boundary reaches a limiting asymptotic value.)

From the definitions:

$$t_D = \int_0^{A_D} Q_{tD} dA_D \quad (9)$$

The preceding equation can be numerically integrated, and the resulting relationship between t_D and A_D is shown as Curve A in Figure 6.

The barrels of oil produced per day is obviously equal to $A_t v / 5.615$, and the barrels of steam injected per day is given by $\dot{Q}_i / f_s \cdot L_v$; therefore the oil-steam ratio at time t , $(O/S)_t$ is equal to $(A_D f_s) / (5.615 \rho c \cdot \Delta T)$, or $(O/S)_t = C_1 \cdot A_D$ where C_1 is a constant characteristic of the thermal conductivity of the reservoir (and boundary rocks) and the steam pressure and quality.

Even after steam breakthrough, the oil-steam ratio should remain constant as long as v remains constant. This is true even though a smaller and smaller fraction of the constant amount of steam being injected will condense within the reservoir.

The velocity of the descending steam zone is not an independent parameter; it is a function of the rate at which the crude oil is heated at the interface between the steam zone and the rate at which the heated layer is swept away by the flowing steam. The physical scaling that is employed in these models includes the explicit scaling factor: $f_s (k_o \cdot v_s / k_s \cdot v_o)$ and the resulting oil-steam ratio should be a function of this parameter if the scaling is correct. In other words, with all other factors remaining constant, the velocity of the descending steam zone, and the oil-steam ratio should be constant as long as the steam quality at the sand face and the kinematic viscosities of the steam and oil (at steam temperature) are constant.

Positive evidence for this conclusion is readily found. The extensive steam floods operated by Chevron¹³ and Getty¹⁴ in the Kern River field indicate only small statistical fluctuations superimposed on a trivial declining oil-steam ratio over as much as ten years of operation after the initial steam stimulation period was completed. The scaled model studies show very small, and gradual declines in oil-steam ratio even as 100% recovery efficiency is approached.

However, the overall oil-steam ratio should also be expected to be a function of the steam required to bring the oil at the interface up to steam temperature; the simplest correlative parametric group is expected to be $(f_s L_v \rho / c_p \Delta T)$.

If the postulated mechanism is correct and the correlative groups have been chosen correctly, then a high correlation coefficient should be found when the oil-steam ratio is correlated against the product of the two preceding dimensionless groups. The usefulness of such a correlation would be very great. It would permit the relative influence of any parameter contained in the dimensionless, correlative groups to be estimated and thereby provide a guide to the relative efficiency of steam drive operations in diverse reservoirs.

C. CRUDE OIL VISCOSITY AND STEAM DRIVE EFFICIENCY

A large number of experiments were made using a model which was a geometrical prototype of five spot patterns which have successfully responded to the steam drive in the Kern River field. The prototype is a 6 acre pattern in a 73.5 foot reservoir with a thickness of 73.5 feet, a porosity of 0.35, and a permeability of 1 darcy. The scaling rules that were employed and the experimental procedures that were used have been already described in great detail¹.

Early experiments in this program confirmed that there is an optimum rate of injection of steam into a five spot pattern that maximizes the oil-steam ratio. The existence of such an optimum had been discovered empirically in field operations by Bursell and Pittman¹⁵ and has also been witnessed in high pressure, scaled steam drive experiments by Huygen and Lowry¹⁶. The optimum injection rate for numerous crude oils in these experiments appears to correspond to injection rates in the range of 100 to 150 barrels of steam per acre per day. The oil-steam ratio is in fact relatively insensitive to the rate in the vicinity of the optimum rate but falls off rapidly as the departure from the optimum exceeds a factor of two, see Table 1.

It is a characteristic of the scaled physical models that one single parameter, such as the crude oil viscosity at steam temperature, cannot be changed without affecting one or more additional parameters. Because of this, it is impossible to conduct a series of experiments in which the crude oil viscosity is the only parameter being varied. In order to study the effect

of viscosity it is therefore necessary to be able to correlate the oil-steam ratio against a group of parameters, of which the viscosity is one, and from the resulting correlation estimate the effect of viscosity by assuming or knowing the values of the other parameters in the correlation group.

The oil-steam ratio that was used for correlation was the instantaneous value that occurred shortly after breakthrough and which then remained substantially constant for a long period of time. Values of the oil-steam ratio prior to this time are strongly influenced by the specific start-up procedures that are used, and by the high heat transfer rates that result from the high temperature differentials that are initially imposed. There is usually little problem in choosing this oil-steam ratio, but sometimes, see Figure 8, some subjective choice is required.

A correlation of the oil-steam ratio against $f_s(v_s/v_o \cdot f_s(L_v/T))$ resulted in a regression with a correlation coefficient of 0.95. However, the correlation was positively affected (the correlation coefficient increasing to 0.98) when the heat term was dropped, see Figure 9. The regression equation is $y = 5.12(x)^{0.57}$. It should be noted first of all that regressions of log-log relationships tend to produce highly optimistic correlations, but correlation coefficients of this magnitude leave little question that the trend indicated by the analysis is correct. Secondly, the fact that the heat term is not important in correlating the results is a strong indication that after steam breaks through to the producing well, the steam drive is primarily governed by fluid drive mechanism. Only a small amount of the injected steam is used for the maintenance of the temperature gradients at the cap rock and the moving boundary between the oil column and the steam. It has already been shown that an inert gas can be substituted for a significant fraction of the steam^{7,17}, after steam breakthrough without significantly affecting the efficiency of the process.

In developing the regression equation, the data points for the two lowest viscosity systems were omitted. The oil-steam ratio has appeared to reach a maximum value when steam finally breaks through to the producing wells in these experiments. A study of the temperature distribution in the models, Figure 10, revealed that at these low viscosities the steam was now developing a frontal drive which is controlled by the rate of heat injection and the distribution of heat in the reservoir, much as supposed in the analytical models. The viscosity of the reservoir fluids now do not control the process, and the oil-steam ratio is independent of the viscosity.

It is to be noted that the oil-steam ratio is a fractional power of the correlating group $f_s(v_s/v_o)$, and if it is assumed that the kinematic viscosity and quality of the steam enter the argument only to the first power; then it would be concluded that the oil-steam ratio is a function of the -0.57 power of the crude viscosity at steam temperature.

The fact that the oil production rate (and therefore the oil steam ratio) appears to be a fractional power of the viscosity merits some discussion. The velocity of the steam vapor is quite high in a steam drive. For example, the injection of 500 barrels of (water converted to) steam per day at a quality of 70% into a reservoir at an average pressure of 200 psi is equivalent to the injection of approximately 4 MMSCFD of an ideal gas. Allowing for an additional 25% of the steam to be condensed at the mid point of a 20 foot thick oil-depleted interval, the vapor velocity will be of the order of 100 feet per day. At velocities of this magnitude it is probable that the applicable form of the Darcy equation should include higher order velocity terms. Scaled model experiments of gas drives in high permeability reservoirs containing low viscosity crudes have confirmed this^{7,17}, and demonstrated that the Darcy equation with higher order velocity terms can be represented by a first order equation (in velocity) if a fractional viscosity exponent is used. The particular value of the exponent appears to be a function of the relative viscosities of the driving and driven fluid, and of the velocity itself. The results of the experiments reported on herein indicate that for the range of conditions encountered in the optimum steam drive operations, the viscosity exponent is 0.57.

D. IMPLICATIONS OF THE REGRESSION EQUATION

The correlation equation that has been developed has serious implications concerning the feasibility of steam drive operations in highly viscous oil reservoirs. For example, suppose that it is required for the profitable operation of a steam drive that the minimum sustained oil-steam ratio must be 0.15 or greater. Using the correlation of Figure 5, it can be calculated that the product of the steam quality and ratio of kinematic viscosities must be equal to 2×10^{-3} or greater. For a steam quality of 70%, the second column of Table 2 shows the maximum viscosity that the crude oil may have at steam temperature if the 0.15 ratio can be reached.

The third and fourth columns show the actual viscosity that would be reached by Kern River crude and Tar 'A' at the corresponding temperatures. An examination of the data in this table leads to the conclusion that reservoirs of Kern River crude oil should yield a 0.15 oil-steam ratio or better at all temperatures above 212°F. On the other hand, tar sand 'A' according to the correlation will yield an oil-steam ratio of 0.15 only when the steam temperature exceeds 550°F.

Although superficially there should be only a small difference in the cost of the heat in a barrel of steam delivered at 550°F compared to the cost of steam delivered at 380°F, there will be a significant practical difference in the efficiency of the steam drive. Thermal losses in the distribution and downhole tubulars when working with high pressure steam are more pronounced in decreasing the quality of the steam that is ultimately delivered to the reservoir. Also, the high temperature and pres-

sure, unless the crude is indeed emulsified, must be maintained within the reservoir right up to the producing well otherwise the influx of oil into the producing well will be seriously impeded as a result of a marked increase in viscosity. Hence, there will be serious production problems that must be overcome to assure that the oil that is mobilized within the reservoir will enter the producing well. Finally, if the required temperature is so high that the latent heat of the steam is seriously reduced, the effect of the heat term, $L_v/\Delta T$, which did not appear significant in the correlation of the experiments reported above, may begin to affect the oil-steam ratio. Hence the correlation does lead to the conclusion that it will be increasingly more difficult to achieve a favorable oil-steam ratio the higher the viscosity of the crude to be recovered.

E. THE EFFECTS OF THICKNESS ON THE STEAM DRIVE EFFICIENCY

If the mechanism presented earlier for the steam drive is reviewed it is apparent that the reservoir thickness does not enter into the dynamic description of the process. It certainly limits the process since when the descending steam zone reaches the base rock no additional oil can be recovered. On the other hand, while the steam zone is expanding downwards there is no reason for the process to be affected by the approach to the base rock other than for the possible differences in the thermal properties of the reservoir rock and the base rock. If the base rock has markedly different thermal properties then the temperature distribution beneath the advancing steam zone will begin to change as the base rock is approached. This will affect the temperature gradient in the oil column and therefore the viscosity gradient in the oil adjacent to the steam zone; the production characteristics can be expected to be altered.

A model of a 27 foot prototype reservoir was constructed and experiments were carried out at the same injection rates as were shown to be optimum for the 73.5 foot model. The data point for the 2 foot model, the square on Figure 5, obviously fits the regression equation very well.

F. THE EFFECT OF INJECTION RATE ON STEAM DRIVE EFFICIENCY

As already noted there is both field and laboratory evidence for the existence of an optimum oil-steam ratio. It is easy to perceive what happens at very low rates of injection: the rate of heat injection is so low that a steam zone is very slow to develop if one develops at all. A low rate of steam injection is equivalent to a hot water drive. The efficiency of such a drive in terms of an oil-water ratio is very poor. (A simple application of the Buckley-Leverett analysis for a water drive in a viscous oil reservoir, even one heated to several hundred degrees would reveal that very large quantities of water are required to displace oil to the residual saturations observed in a steam drive.) As the steam injection rate continues to increase, a steam zone and eventually the steam drive is developed and the unique efficiency of such a drive is realized.

However, what happens at high rates of injection is not as readily perceived. It is obvious that with increasing velocity a unit mass of steam is losing its ability to transport the heated oil. The probable reason for this is a decreasing ratio of the relative permeability of the relatively viscous driven crude to that of the highly mobile driving steam vapor. Rose¹⁸ reported on experiments which pointed to this effect, and more recently the phenomenon has been studied in great detail using physically scaled models^{7,17}.

The parameters of the runs shown in Figure 7 were not all identical, see Table 1. As already noted, the physical scaling used with the vacuum models precludes changing only one variable at a time. However, as shown in Table 2, the scaling parameter, $f_s(v_s/v_o)$ varied over only a small range. Thus, it is seen that rate, steam quality, and the kinematic viscosities of the steam and of the crude at steam temperature are the chief determinants of steam drive efficiency.

When assessing the effect of injection rate on the sustained oil-steam ratio that may be anticipated after steam breakthrough, it is important to separate the effect from the initial response that may be observed in a steam flood. In actual operations, the initial production performance of a steam drive is strongly influenced by the steam stimulation (cyclic injection of steam into producing wells) which almost universally precedes the eventual implementation and breakthrough of continuous steam injection.

G. APPLICABILITY OF FINDINGS TO STEAM DRIVE OPERATIONS

The results of this study, limited as they may be, do point to several novel conclusions concerning the efficiency of the steam drive under a range of conditions that have not been previously reported.

The results of the study show that when steam override is the dominant feature of the steam drive process, the thermal efficiency, which is also equal to A_D , will reach a maximum value at steam breakthrough. Thereafter, the thermal efficiency will decrease steadily¹⁹ although the oil-steam ratio may remain constant if the velocity of descent of the steam zone is constant. Usually, the initial injection rate in a steam drive should be as high as possible in order to establish the steam zone across (temperature) reservoir. This leads to a still higher thermal efficiency at the time of breakthrough. After breakthrough, the injection rate and injection pressure need to be optimized simultaneously because of the sensitivity of the ratio to both rate and the ratio of kinematic viscosity of the steam to that of the crude oil at steam temperature. Thermal efficiency, per se, is not the critical factor in the efficiency of a steam drive.

The effect of the viscosity of the crude at steam temperature, which did not appear in the early analytical model for the steam drive, is revealed to be very pronounced. It follows that

the exploitation of truly viscous crudes, tar sands and bitumens by the steam drive may be more difficult than has been generally presumed. The pronounced success of the steam drive to date may be due to a fortuitous correspondence of the kinematic viscosities of steam and San Joaquin Valley crude oils. If this is validated, then the exploitation of bitumens and tar sand reservoirs by a steam drive may become feasible only when further devices for enhancing the drive are developed.

On the other hand, the results point to the possibility that reservoirs of high gravity crudes, even those containing residual saturations, may be effectively exploited by the steam drive. The mechanism of oil recovery in such reservoirs does change to that of a frontal displacement and oil-steam ratios are very high. Figure 11 shows the results of a scaled model study of a steam drive in a reservoir containing a residual saturation of 22% of a high gravity crude. The oil-steam ratio is above 0.2 after recovering 40% of the oil in place at the beginning of the drive. The high value of the oil-steam ratio however may not assure that economic viability will be attained. A favorable oil-steam ratio only indicates a favorable use of energy, viz., significantly more energy is recovered than is injected. However, an important factor in the economics of such a recovery process is the amount of oil that can be recovered per well. In the United States, the high gravity reservoirs are thinner than the relatively recent accumulations of viscous oil, and at residual saturation the amount of oil per acre is relatively small. Whether a particular reservoir has the required features to justify a steam drive operation must be decided on a case-by-case basis.

The results also point to the probability that thin reservoirs can be exploited by a steam drive and yield virtually the same oil-steam ratios that are realized when exploiting thicker reservoirs. This conclusion should be true for any reservoir in which the net steam rate per well is the same as it is in thicker reservoirs and in which the steam overrides the oil column. In all reservoirs in which the steam flow is stratified above the oil column, the resulting oil-steam ratios will be significantly less than those predicted by analytical models; the discrepancy being greater the thicker the reservoir. Thick reservoirs, in the late life of a steam drive, will show a progressive decline in oil-steam ratio due to the segregation of steam and the steam condensate which will tend to isolate the flowing steam from the oil column. The development of an oil in water dispersion or emulsion at the boundary would be a great boon in maintaining the efficiency of the steam drive in such systems.

H. CONCLUSIONS

The scaled physical model experiments of the steam drive that have been reported herein indicate that the viscosity of the crude oil is a very important parameter in affecting the efficiency of the process. The results raise some concern about the applicability of an unassisted steam drive to be capable of

economically recovering very viscous crudes, tar sands and bitumens.

The results also indicate that thin reservoirs will yield oil-steam ratios which are as high if not somewhat higher, at the conclusion of the operation, than that achieved in exploiting thick reservoirs of viscous crude oils provided that the injection rates per unit pattern area are as high as they are in thicker reservoirs.

The energy efficiency with which steam can displace low viscosity crudes, even at residual saturations, appears to be greater or comparable to that which can be achieved in current operations with moderately viscous crudes in thick reservoirs.

After steam breakthrough, the steam drive appears to be governed by the same features that govern a high velocity gas drive; only a small fraction of the injected steam is used in maintenance of the appropriate boundary temperature in the reservoir. If the reservoir fluids have a sufficiently low viscosity they are frontally displaced and high oil-steam ratios can be achieved in contrast to the overlay of the steam and lower oil steam ratios that are developed when injecting steam into reservoirs of viscous oil.

VI. DEFINITION AND ENHANCEMENT OF THE STEAM DRIVE

The classic view of the steam drive⁸ is of a steam zone developing across the entire cross section of the reservoir; the oil saturation being reduced to some low level by frontal displacement. Such a view is incorrect for viscous crudes since a bank of viscous oil cannot be displaced at a significant rate under the pressure gradients employed.

The results of both field operations^{12,17} and scaled physical model studies (see Section IV) demonstrate that the steam channels through the reservoir, usually overlaying the oil column, and sweeps or drags the underlying oil to the producer. Our own observations and those of others¹³ suggest that emulsification of the oil by the condensing, high velocity steam is a factor contributing to the mobilization of the heated oil.

Since steam flowing through the reservoir across the top of the oil column will not interact with the base rock for some time, there is no reason to believe that thickness, above some minimal value, will affect the results of a steam drive. Physical model studies and field results indicate a general insensitivity to thickness, Figure 12.

Since it is the dynamics at the steam oil interface that controls the mobilization of the oil, it is the viscosity of the oil at steam temperature that affects the production rate of a steam drive. However, as the oil viscosity at reservoir temperature decreases to a sufficiently low level, the steam drive changes its character and frontal displacement occurs. This is apparent from the temperature distribution in the scaled model studies. The displacement of the crude is now controlled by the rate of injection of steam and exhibits little dependence on the oil viscosity. It is only in laboratory experiments that a sufficient range of viscosities in otherwise identical systems can be investigated to develop proof for these hypotheses, Figure 9.

The conceptualization of the steam drive that follows from the foregoing observations leads to the conclusion that a sufficiently low viscosity oil should be as effectively displaced by a high velocity gas drive as viscous oils are displaced by steam. (4 MMSCFD of a gas would be equivalent to 500 barrels of 200 psi steam, before any condensation. The gas velocity into a 50% depleted, 5 acre pattern of a 50 foot thick sand would average well over 100 feet per day.)

To verify this, two suites of experiments were run. In one series, the steam drive was interrupted after steam breakthrough had been achieved and nitrogen was a) alternated with steam injection and b) injected simultaneously with a proportionally reduced rate of steam injection. The results, Figure 13, show

that the substitution of nitrogen for some of the steam resulted in an improved oil-steam ratio for the same volume of steam injected. In other words, the nitrogen, as a partial substitute for the steam, was effective in continuing the displacement of the already heated oil at the vapor-liquid interface.

Finally, a series of runs were done in scaled models in which low viscosity oils were displaced by nitrogen, alone. The results, Figure 14, show the marked effect of viscosity on the displacement of the crude, much as is observed in the steam drive. With the lowest viscosity fluid, although the override is still present, so much of the fluid is displaced in so short a time, the displacement is virtually frontal.

It is of interest to note that the k_{ro}/k_{rg} ratio that is derived from such experiments, Figure 15, is dependent on velocity as would be expected at high velocities where stratified flow occurs²¹. These results can be correlated by including higher order terms in the Darcy equation²³, or by using an exponential viscosity term to absorb the higher order terms, Figure 16.

These continuing studies on the manner in which steam drive displaces crude oil have indicated the potential for extending its use to relatively thin reservoirs and reservoirs containing high gravity crudes, and in addition the possibility of realizing greater profitability by substituting some inert gas for steam in the mature life of the operation.

NOMENCLATURE

A	projected horizontal area of steam zone, ft^2
c	specific heat, $\text{BTU/lb}/^{\circ}\text{F}$
f_s	steam quality
k	permeability, mds.
L_v	latent heat of steam, BTU/lb
O/S	oil-steam ratio barrels oil/barrels of water converted to steam
Q	rate of heat injection, BTU/day
Q	cumulative heat, BTU
t	time
t	time at which steam zone reaches the area element, dA
T	temperature, $^{\circ}\text{F}$
v	velocity of decending steam zone, ft/day
α	thermal diffusivity, ft^2/day
λ	thermal conductivity, $\text{BTU/ft/day}/^{\circ}\text{F}$
ν_o	kinematic viscosity of oil, centistokes
ν_s	kinematic viscosity of steam, $\text{ft}^2/\text{sec } 10^3$
ρ	density, pounds/ft^3

Subscripts

cr	cap rock
D	dimensionless
o	oil
oc	oil column
r	reservoir
s	steam
sz	steam zone
t	total

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TABLE 1
MODEL DATA FOR REPORTED EXPERIMENTS

Run No.	Temp. °F	f_s	v_s^1	v_o^2	$f_s(v_s/v_o)^3$	O/S
1 ⁴	140	0.071	0.841	150	3.98×10^{-4}	0.060
2	182	0.171	0.330	85	6.63×10^{-4}	0.088
3	159	0.151	0.535	76	1.06×10^{-3}	0.094
4	179	0.270	0.351	38	2.37×10^{-3}	0.150
5	186	0.245	0.306	28	2.68×10^{-3}	0.170
6	156	0.176	0.572	41	2.43×10^{-3}	0.185
7	171	0.158	0.413	22	2.94×10^{-3}	0.23
8	192	0.245	0.273	9.0	7.43×10^{-3}	0.30
9	180	0.268	0.344	3.4	2.71×10^{-2}	0.40
10	180	0.256	0.344	1.8	4.89×10^{-2}	0.40
84 ⁵	149	0.195	0.674	110	1.19×10^{-3}	0.088
132	159	0.151	0.535	76	1.06×10^{-3}	0.094
240	187	0.141	0.300	28	1.51×10^{-3}	0.090
478	207	0.121	0.209	18	1.41×10^{-3}	0.063

¹ft²/sec X 10³

²centistokes

³The prototype has the same value of this dimensionless group.

⁴Runs 1 to 10 are at prototype "optimum" rate of 130-150 BWD

⁵Run designation is the prototype BWD/acre.

TABLE 2
COMPARISON OF REQUIRED VISCOSITY TO ATTAIN OIL-STEAM RATIO OF
0.15 WITH VISCOSITIES OF A KERN RIVER CRUDE AND BITUMEN
EXTRACT FROM TAR SAND "A"

Temp. °F	Viscosity, csks.		
	Maximum Value To Achieve $O/S = 0.15$ $f_s = 70\%$	Kern River Crude	Tar "A"
212 (15 psia)	67	72	300
300 (67 psia)	19.6	18.5	40
382 (200 psia)	8.3	7.0	14.5
450 (423 psia)	5.8	4.5	8.0
550 (1045 psia)	2.3	---	2.9

FIG. 1. ILLUSTRATING THE BASIC MECHANISM FOR RISING STEAM.

FIG. 2. ILLUSTRATING THE BASIC MECHANISM FOR THE STEAM DRAG PROCESS

FIG. 3

FIG. 4

FIG. 5 CONCEPTUALIZATION OF GROWTH OF OVERRIDING STEAM ZONE

FIG. 6. DIMENSIONLESS AREA AS A FUNCTION OF DIMENSIONLESS TIME (EQUATION 9).

STEAM INJECTED, EQUIVALENT WATER, P.V.'s

FIG. 7. OIL-STEAM RATIO HISTORY AT VARIOUS INJECTION RATES, SEE TABLE 1

FIG. 8. OIL PRODUCTION IN REPRESENTATIVE EXPERIMENTS, SEE TABLE 1

FIG. 9. CORRELATION OF OIL-STEAM RATIO AS A FUNCTION OF PRODUCT OF STEAM QUALITY AND RATIO OF KINEMATIC VISCOSITIES.

FIG. 10. TEMPERATURE DISTRIBUTION AFTER INJECTION OF ONE PORE VOLUME, INJECTION WELL AT RIGHT.

TYPICAL OVERRIDE WITH HIGH VISCOSITY OIL

ALMOST FRONTAL DISPLACEMENT WITH LOW VISCOSITY OIL.

FIG. 11. OIL-STEAM HISTORY FOR RESIDUAL, LOW VISCOSITY CRUDE OIL.

FIG. 12. OIL/STEAM RATIO IN FIELD OPERATIONS AND SCALED PHYSICAL MODEL STUDIES (DOTTED BAND), COMPARED WITH ANALYTICAL PREDICTIONS BASED ON FRONTAL ADVANCE (SOLID LINE).

FIG. 13. EFFECT OF SUBSTITUTION OF NITROGEN ON OIL/STEAM RATIO AFTER STEAM BREAKTHROUGH IN SCALED PHYSICAL MODEL

FIG. 14. EFFECT OF OIL VISCOSITY ON VERTICAL SWEEP BY HIGH VELOCITY INERT GAS (NITROGEN).

FIG. 15. EFFECT OF RATE ON MACROSCOPIC RELATIVE PERMEABILITY RATIOS FOR EXPERIMENTS REPRESENTED BY FIG. 4.

$$q = f \left[\mu - (a\mu^m + b) \right]$$

FIG. 16. EFFECT OF VISCOSITY ON EXPONENT "m" IN EXPANDED DARCY EQUATION FOR EXPERIMENTS REPRESENTED BY FIG. 4.