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LABORATORY INVESTIGATION OF THE STEAM DISPLACEMENT PROCESS IN A UTAH TAR SAND

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A LABORATORY INVESTIGATION OF THE STEAM DISPLACEMENT PROCESS IN A UTAH TAR SAND

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ABSTRACT

Laboratory experiments are being conducted to study the potential of high pressure [(350-1000 psig) (2400-6900 kPa)] steam displacement as an oil recovery process for Utah tar sand. These one-dimensional displacement experiments are designed to identify the relationships between the recovery efficiency and the processing conditions for two grades of tar sand representing different reservoir properties. The processing variables are the steam flowrate and initial tar sand preheat temperature; the controlled reservoir properties are the saturated permeability, porosity, bulk density, and the initial oil saturation.

Crushed samples of tar sand are uniformly and consistently packed to physical properties closely resembling reservoir conditions. This is accomplished using an automated pneumatic-hydraulic tube packing apparatus. Tar sand containing 7.7 or 11.4 wt.% bitumen is packed to permeabilities ranging from 70-1100 millidarcies (0.07-1.1 μm^2) with oil saturations of 45-70% of pore volume (PV). The corresponding porosity ranges from 32-36%.

Preheat temperatures from 215-475°F (102-246°C) are initially established before saturated steam is injected at flow rates of 4.5-14.5 cc/min (0.6-1.92 lbs/hr) with a controlled backpressure of 360-390 psig (2500-2700 kPa). Results are presented from fifteen experiments, including the determination of various chemical and physical properties of the bitumen and the thermally produced oils. In addition, results and operating conditions related to the automated tube packing apparatus are discussed.

INTRODUCTION

Prompted by the energy crisis, 1973 marked the beginning of several U.S. Department of Energy laboratory studies and three field tests investigating the in situ thermal processing of Utah tar sand. These field tests[1-3] investigated reverse and forward combustion as well as the steamflood process for oil recovery. Common to all in situ operations, the recovery efficiency depends on an appropriate match between the reservoir properties and the selected processing variables.

Reverse combustion is considered more applicable than forward combustion within extremely viscous oil and tar sand reservoirs. Reservoir plugging is reduced and sufficient air can be injected countercurrent to the flame front to maintain combustion. Initially the air flows through an unaffected reservoir region into the advancing flame front where the majority of oxygen is consumed. The resulting product gases drive (at improved mobility ratios) the cracked and thermally upgraded oil, having a much reduced viscosity, through the preheated zone behind the flame front where it can be conventionally recovered.

Although gravity override and poor sweep efficiency remain severe problems, conventional steam flooding of a heavy oil can usually be accomplished at less than reservoir fracture pressures because of a favorable mobility ratio. This mobility ratio is principally due to the higher permeabilities of an unconsolidated reservoir, typical of Kern River steamfloods, accompanied by a significant oil viscosity reduction with temperature. Because steam must preheat the reservoir as well as displace oil, recovery of oil during a conventional steam drive results from sequential displacement by cold water (condensed steam), followed by progressively hotter water until the arrival of the steam front where the temperature is dependent on the allowable overburden pressure. Willman et al.[4] experimentally determined the existence of the following steam drive displacement mechanisms: 1. temperature induced oil viscosity reduction (improved mobility ratio), 2. thermal swelling of the oil, 3. steam distillation, 4. solvent extraction of the original oil by recondensed light hydrocarbon distillates, and 5. gas drive effects.

As described by Ehrlich[5], significant differences exist between this idealized steam drive and a steam drive within tar sands such as those of Utah, Texas, or Canada. The very low initial oil mobility prevents simultaneous reservoir heating and oil displacement. Preheating the tar sand reservoir must first be accomplished to provide a means for the establishment of a flow path between the injection and the production wells. Development of this heated flow path has been accomplished by steam injection into the underlying highly permeable water zones at Peace River, Canada, and by generating steam induced fractures in a Texas tar sand. Other techniques could possibly include electrolinking or a reverse combustion through a thin mid-section of a tar sand zone. Properly conducted, in situ reverse combustion could generate sufficient heat within this thin reservoir section to ultimately preheat the remaining saturated formation, substantially reduce the bitumen viscosity, and create a heated flow path. This prepares the reservoir for subsequent steam displacement, which has a much improved mobility ratio over the air.

As previously mentioned, several laboratory investigations have been conducted, but unfortunately, they have not been able to simulate actual reservoir conditions. These investigators[6-8] used manually packed tar sand tubes containing saturated permeabilities ranging from 3 to 250 times greater than observed in cores. Porosity in one study ranged from 40-46% and in another study ranged from 48-56%. Not only are these conditions unrealistic, but also large porosity variations between series of similar lab tests occurred. And of course, as the porosity increases for a constant weight percent bitumen in the tar sand, the oil saturation proportionately decreases. In one of these earlier laboratory studies, the initial oil saturation was only slightly higher than the expected residual oil saturation.

Because of these problems, much of the effort in this current laboratory program has been devoted to the development of improved experimental techniques for the study of the steam drive process. A significant improvement in obtaining consistent reservoir properties has been the development of an automated device which reproducibly packs tar sand into laboratory tube reactors. Additionally, the ability to select and control specific physical properties of the tar sand pack within the tube permits rapid screening tests to be conducted. Both minimum permeability and tar sand preheat temperature screening for the steam displacement process is being conducted in support of future WRI large-scale 3-dimensional experiments. These "block reactor" studies will investigate thermal processes at up to 1000 psig (6900 kPa) within a 2 ft^3 (0.6 m^3) block of consolidated tar sand.

This paper presents the results of a series of linear steam displacement experiments conducted at varying injection rates and preheat temperatures on two grades of a Utah tar sand packed to specific physical properties. Preheat temperatures above and below the temperature of the injected steam are investigated. Both isothermal (early steam drive) and adiabatic (reservoir condition after continuous and lengthy steam injection) boundary conditions are utilized. Also briefly discussed is the automated tube packer.

EXPERIMENTAL APPARATUS

Tube Packer

This automated tube packer is designed to control those variables identified during previous manual packing exercises as being responsible for poor reproducibility. Both inhouse and outside experiences[9] have been considered. The packing variables are 1. the incremental tar sand weight introduced into the tube, 2. the downstroke compaction force, 3. the number of cyclic strokes per increment, and 4. the temperature (heated/frozen) of the tar sand feed.

The automated packing device is schematically illustrated in Figure 1. It consists primarily of a 4 ft. × 14 ft. (1.2 m × 4.3 m) metal frame, 6 in. I.D. × 36 in. (15 × 91 cm) long hydraulic cylinder and power unit, 6 in. I.D. x 2 in. (15 × 5 cm) long pneumatic cylinder with tamper, and various instruments and controls. The device currently is used to pack tar sand into 3-5/16 in. I.D. × 32 in. (8.4 × 81 cm) long reactor tubes, but it can be adjusted for cylinders ranging in size from 2 to 6 in. I.D. (5 to 15 cm) and up to 36 in. (91 cm) long. Tar sand, crushed to less than 1/2 in. (1.3 cm) and riffled to provide uniform mixing, is incrementally added to the reactor tube and compacted by a tamper which closely fits inside the tube. The compaction force of this tamper is adjusted by regulating the air supply pressure to the reciprocating pneumatic cylinder up to a maximum air pressure of 250 psig (1700 kPa). Each 2-inch (5 cm) downward stroke of the tamper compacts the tar sand. The number of strokes per tar sand increment is controlled through adjustments to three timers. These timers specify total packing, tamper up, and tamper down durations. Packing automatically stops at the preset total time, thus permitting the addition of the next increment. The hydraulic cylinder controls the vertical movement of the tube being packed. It lowers the tube prior to adding tar sand and raises the tube to bring the recently added and unpacked tar sand into contact with the tamper. There is an override switch on the hydraulic power unit which prevents the tube from being raised unless the pneumatic cylinder is freely hanging approximately 1/2 in. (1.3 cm) below the main frame. As the tar sand contacts the tamper, the pneumatic cylinder is lifted off an electro-mechanical switch disengaging the hydraulic power unit. Two small pneumatic lifters then pull the pneumatic cylinder into secure contact with the frame. The start button is pressed to repeat the timed packing sequence.

Steam Displacement Apparatus (SDA)

A schematic diagram of the laboratory steam displacement apparatus is shown in Figure 2. The reactor tube (4-3/8" O.D., 3-5/16" I.D. × 32" L) (11, 8 × 81 cm) is constructed of 347 SS forgings and rated for 3700 psig at 950°F (25500 kPa, 510°C). It is vertically housed within five pairs of wrap-around shield heaters which are hinged within a quick opening, insulated shell. Five pairs of internal/external thermocouples are connected to individual heater controllers and designed for isothermal (preheat) or adiabatic boundary conditions. The out-of-phase thermocouple arrangement limits the energizing of an adiabatic heater only after the steam temperature has been sensed by the subsequent internal thermocouple. Artificial driving of the steam front is thus minimized. The internal thermocouples (1/16" O.D.) (0.16 cm) are spaced approximately 6 inches (15 cm) apart within the center of the packed tube and radially secured through side wall pressure fittings.

The reactor backpressure is controlled by a combination of nitrogen buffer gas and a flow control valve on the high pressure gas/liquid separator. Positive displacement pumps inject steam up to 1000 psig (6900 kPa) into the top of the packed tube. The steam generator is constructed of 40 feet of 1/4 inch O.D. (12 m × 0.6 cm) stainless steel tubing wound around a 34 inch × 1-1/2 inch (86 × 3.8 cm) diameter aluminum bar and placed inside an insulated cylindrical heater. A heater controller is set to generate superheated steam. However, the superheated steam gradually looses quality and enters the packed tube at 95-99%. A 24 inch section of line immediately ahead of the packed tube is insulated and wrapped with heating tape for added assurance of a high steam quality.

Gas metering and control equipment for CO_2, N_2, and air has been installed for future studies involving combinations of combustion and steamflooding. Gases and steam may be injected either sequentially or simultaneously as in air/steam co-injection. This equipment also functions as a gas permeameter for screening the packed tubes for acceptability in thermal recovery experiments.

The entire system is instrumented and interfaced to a data acquisition computer which records temperatures, pressures, and flowrates every five minutes and generates hourly hardcopy output.

EXPERIMENTAL PROCEDURE

Seventeen 500-gram increments of Asphalt Ridge tar sand at ambient temperature are automatically packed into a reactor tube using the previously described tube packer. Three additional samples, representing tar sand that was packed into the top, middle, and bottom of the tube, are taken for oil and water analysis quality control. After packing is complete, the final charged weight is adjusted for any tar sand that may be adhering to the tamper of the tube packer.

The physical properties of saturated permeability, porosity, bulk density and oil saturation are determined for each packed tube. Suitable specific ranges of these values are determined before the experiment. An air permeameter, interfaced to a computer, enables rapid measurements to be routinely performed on the entire packed tube. Six to ten separate measurements at inlet pressures ranging from 5 to 30 psig (35 to 207 kPa) are automatically averaged to determine the saturated permeability to air. The remaining physical properties are calculated.

Approximately 1 inch (2.5 cm) of a coarse sand (12-20 mesh) is placed on top of the tar sand in an acceptably packed tube to provide for more uniform steam distribution. A stainless steel wire mesh screen in placed at the bottom of the tar sand to minimize sand production and prevent the washing out of the packed tube. The tube is pressure checked and five evenly spaced, thin strips of insulation are wrapped around it. This insulation minimizes the vertical convective heat transfer within the annulus between the tube and the shield heaters.

Tube preheat and steam generation within a test loop are activated simultaneously. When the correct internal preheat temperature is established, the steam test loop is shut in and all steam is diverted into the top of the packed tube. Appropriate backpressure control of 360-390 psig (2500-2700 kPa) is immediately established and the steam injection pressure is permitted to rise to that pressure [less than 1000 psig (6900 kPa) system design limit] necessary to overcome the combination of the packed tube pressure drop and the backpressure. Boundary conditions of isothermal (preheat set points) are either maintained or adiabatic conditions are established.

Product samples of oil and water are manually collected every two hours from three collection knockouts. However, due to the backpressure control system and steam being a condensable gas, approximately 90% of the liquid collected is recovered from the high pressure gas/

liquid separator. Produced water which readily separates from the oil is weighed and combined for future analyses. The more stable emulsions require one of two solvent separation techniques to isolate the oil. Gas samples, infrequently taken during the steam runs, will become more important during the combustion and steam/air co-injection experiments. Steam injection is generally stopped after the production of the oil bank and when the water-oil ratio exceeds 500:1. The packed tube is slowly depressured and allowed to cool to ambient temperature before a final post experiment permeability is measured. The tar sand is hydraulically pressed from the tube, weighed, and top, middle, and bottom sections are analyzed for fluid saturations.

Analytical Methods

The sand and water is removed from the bi-hourly oil production samples by one of two methods: 1. the production sample, less free water, is diluted with toluene, filtered through glass-fiber paper (GF/A), and the toluene and water removed from the oil at reduced pressure, or 2. the production sample, less free water, is diluted with toluene, and centrifuged at 2000 rpm for one hour. In the former case the produced oil is measured directly in a tared flask. In the latter case it is measured by subtracting the weight of sand and water. An oil production curve versus time or pore volumes of steam injected is generated and samples are selected for simulated distillation analysis.

Post test core samples are also obtained from the top, middle, and bottom of the reactor. These samples are Soxhlet extracted with toluene until the hot extraction solvent becomes colorless and the resulting solution is then filtered through glass fiber paper to remove traces of fine sand. The toluene is removed from the oil at reduced pressure. The weight percent original bitumen is similarly determined using Soxhlet extraction or burning off the bitumen at 900°F (482°C) for sixteen hours in a muffle furnace. Agreement between these two methods is better than 0.2 weight percent bitumen. Simulated distillation analysis is also performed on these samples.

DISCUSSION AND RESULTS

Tube Packer

The capability of the tube packer to generate packed tubes which simulate reservoir properties is clearly observed by comparing the packed tube data for Asphalt Ridge Quarry tar sand with actual reservoir core data from the adjacent tar sands at N.W. Asphalt Ridge (Table 1). Only a 2-11% variance exists between the packed tube physical properties (bitumen saturation, porosity and bulk density) and the weighted average core data from six and seven random wells. Saturated permeabilities are within the same order of magnitude. The average tar sand core data from the sites of the three U.S.D.O.E. field tests (LERC 1C, LERC 2C, and LETC 1S) are also displayed for comparison.

Although the properties of the packed tar sand closely resemble the core samples, there remains the potential for further improvements. This may be accomplished by increasing the number of packing strokes or decreasing the tar sand incremental charge rate.

No crushing or distortion of the sand grains as a result of the tamping action by the tube packer is apparent. Sand grain sieve analyses were performed on both the 7.7 and 11.4 wt.% bitumen tar sand. The cumulative grain size distributions are plotted in Figure 3. Similar analysis from a North Kern Front Field, Bakersfield, California, currently undergoing thermal (steamflooding) recovery, is included for comparison. Sieve analysis was also performed on steamflooded sand recovered from four packed tubes containing the original 7.7 wt.% tar sand. The tar sand was removed from these packed tubes and the bitumen and sand separated. The results of the sieve analyses coincide exactly with the curve for the 7.7 wt.% tar sand.

The reproducibility of the reconstituted tar sand properties has also been demonstrated by packing 14 tubes under the identical tube packer conditions. For this test, 500 gram increments of tar sand containing 7.7 wt.% bitumen were compacted to total lengths of 16-31 inches (40-80 cm) within the reactor tubes. Each increment of tar sand was individually compacted by 50 tampings with 225 psig (1550 kPa) of air pressure in the pneumatic cylinder. At these conditions, the saturated permeabilities of all 14 tubes were in the range of 1.05 ± 0.08 darcies (1.05 ± .08 μm^2) and the porosities were 32.1 ± 0.6%. The corresponding bulk densities were nearly constant at 1.97 ± 0.02 gm/cc, and the bitumen saturations were 47.4 ± 1.3% PV.

Steam Displacement Apparatus (SDA)

Material studied within this report is confined to outcrop samples obtained from Asphalt Ridge, Utah. This tar sand is generally considered oil wet, with water saturations less than 0.5 wt.%. A partial summary of physical properties for the fifteen mechanically packed tubes, which were steamflooded, is listed in Table 2. Basically two grades of tar sand, 7.7 (two experiments assayed leaner at 7.4 wt.%) and 11.4 wt.% bitumen are used. The 7.7 wt.% tar sand produces the more permeable packing of approximately 1.0 darcy (1 μm^2) with oil saturation ranging from 44 to 48% PV. The richer, 11.4 wt.%, tar sand yields simulated core packs of less than 0.55 darcy (0.55 μm^2) with oil saturations ranging from 61 to 68% PV. The permeabilities between 0.07 and 0.33 darcy (0.07 - 0.33 μm^2) are intended for "block reactor" minimum permeability screening.

These fifteen laboratory experiments are subdivided into four categories. The first category compares the steamflood response to isothermal and adiabatic boundary conditions. Results of a steam drive within a rich tar sand, possessing low permeability and high oil saturation, versus a leaner tar sand, containing greater permeability and lower oil saturation, is studied within the second group. Variations in the process conditions of preheat temperature and flowrate are considered in the third group. Preheat temperatures of 215, 300, 325, 400 and 475°F (100, 150, 160, 205 and 246°C) are studied for optimization and the flowrates ranged from 4.5 to 14.5 cc/min (0.6-1.9 lbs/hr). The fourth category represents the minimum permability screening for a large 3-dimensional reactor designed with a 1000 psig (6900 kPa) pressure ceiling. Table 3 summarizes the operating conditions, the oil recovery, and the residual oil saturation results.

All experiments, except SDA 012, 014, and 015, experienced sufficient steam breakthrough to establish reliable residual oil saturations. Oil production typically begins prior to steam breakthrough with the cumulative recoveries dependent on the initial preheat temperature, steam flowrate, total pore volumes of injected steam, and heating mode (isothermal or adiabatic). After breakthrough, the tube temperature remains constant at the steam injection temperature and the oil production declines.

Isothermal Versus Adiabatic Boundaries

Isothermal control results in maintaining the heater shields surrounding the packed tube at a specific temperature regardless of the injected steam temperature. This condition represents the reservoir at the beginning of a steamflood, after the establishment of a heated path between the injection and production wells. Adiabatic control is established when the heater shield temperature tracks the temperature rise due to steam migration within the packed tube. This condition represents a well established steam drive.

Typical steam front velocities for the isothermal boundary condition range from 3 to 10 ft/day (1-3 m/day). This thermal front movement is shown in Figure 4 where the internal thermocouple temperatures are plotted versus time. Thermocouple #2 is the uppermost within the tube. More rapid steam front velocities ranging from 13 to 45 ft/day (4 - 14 m/day) exist for the adiabatic boundary.

These higher steam front velocites obviously accelerate the entire steam drive process resulting in a more rapid oil production profile. Although both boundary conditions simultaneously exist at different locations within an in situ steam drive, the adiabatic mode may be perferred within the laboratory because it tends to give similar results with reduced experimental time. Figures 5 and 6, representing the steamflood cumulative oil recovery in percent of original-oil-in-place (% ooip) versus pore volumes of steam injected for isothermal and adiabatic boundary conditions, demonstrate this effect. Approximately 15% of the OOIP is produced after injecting 5 pore volumes of steam as compared to 30% OOIP recovery for the adiabatic boundary conditions. Table 3 also supports this argument because the percent oil recovery and the residual oil saturation (S_{or}) are independent of the heating mode.

Tar Sand Grade

There are two very noticeable differences when comparing steam drive performance in a rich grade (11.4 wt.%) to a leaner grade (7.7 wt.%) tar sand: 1. increased oil yield and 2. reduced permeability resulting from the thermal swelling of the oil. The cumulative percent oil recovery for the 11.4 wt.% tar sand approaches 50% OOIP between 12 and 21 PV of injected steam (Figure 7), but for the 7.7 wt.% grade the oil recovery is approximately 35% OOIP (Figure 8). This factor is related to the S_{or} being independent of the initial oil saturation.

Operationally, initial differential pressures across the packed tar sand bed, prior to steam breakthrough, ranged from 30-100 psig (205-685 kPa) for the lean and at least double that, from 100-200 psig, (685-1370 kPa), for the rich, 11.4 wt.% tar sand. The steam injection, controlled reactor discharge, and the calculated differential pressures for a typical steam displacement experiment, SDA 018, are plotted in Figure 9. Generally a 10-30 psig (70-205 kPa) pressure drop remained after steam breakthrough for the lean and approximately 50 psig (340 kPa) for the richer grade. The higher pressures for the richer grade are attributed to the increased thermal volumetric expansion of the oil into the gas saturated pore space which further reduced the permeability. The thermal swelling characteristics of the bitumen, determined from measured specific gravities, is plotted versus temperature as the specific volume percent change (Figure 10). The magnitude of this very significant steam drive recovery mechanism is also demonstrated by comparing the early incremental oil production from SDA 016 at the rich grade (Figure 11) with the leaner grade experiment SDA 021 (Figure 12). The incremental oil production at 1.2 pore volumes was double for the richer grade. Additionally, at 3 pore volumes, where the two cumulative percent oil recovery curves cross, approximately 45% more oil was recovered from the richer grade tar sand. Although the influence of viscosity reduction is identical (same preheat temperature), additional recovery due to steam distillation, solvent extraction and gas drive cannot be discounted. The benefits of thermally induced viscosity reduction are shown in Figure 13 for the Utah and Athabasca tar sands and a California heavy oil.

Residual Oil Saturations

The steamflood residual oil saturation (S_{or}) for the Asphalt Ridge (oil wet) tar sand consistently ranged around 30% PV regardless of the initial oil saturation, preheat temperature, or steam injection rate. This compares to a reported S_{or} of 10% PV for the Kern River, California, heavy oil and 20% PV for an Athabasca, Canada, (water wet) tar sand.

Not surprisingly, this S_{or} is largely dependent on the final steam temperature within the packed tube. For all experiments this temperature was approximately 450°F (232°C), and the backpressure was controlled at 360 - 390 psig (2500 - 2700 kPa). This dependence on temperature is observed within the final 20% of the operation of SDA 009 when the heater shield controllers artificially increased the steam temperature from 450 to 700°F (232 - 371°C). This resulted in a 46% increase in oil production (refer to Figure 6) and a final S_{or} of 21% PV.

Preheat Temperature

The initial preheat temperatures for the tar sand pack are 400, 475, and 300°F (205, 246, 150°C) for the three rich grade experiments (SDA 016, 017, and 018). Beneficial effects from increased preheats are only anticipated to be effective prior to steam breakthrough. After breakthrough, the entire tar sand bed becomes the same temperature as the injected steam (approximately 450°F, 232°C). This hypothesis is confirmed in Figure 7, where the initial rate of oil recovery progressively increase for increasing preheat temperatures. The influence of preheat ceases after 6-7 pore volumes, which coincides with the steam breakthrough region for the three experiments.

After steam breakthrough, the preheat effects are not obvious. The 475°F (246°C) preheat experiment (SDA 017), although the best producer prior to steam breakthrough, approaches a 40% cumulative oil recovery while the other two experiments yield 50% OOIP at approximately the same pore volumes. Lack of remaining steam distillable hydrocarbons after breakthrough is being investigated as a possible explanation. With respect to the thermal swelling of the bitumen, there are slight increases in the steam injection pressure as a function of higher preheat temperatures. Since experiment SDA 013 was operated in the isothermal mode it is not considered.

The three lean grade experiments (SDA 019, 020, and 021) were conducted at initial preheats of 400, 475, and 400°F (205, 246, 205°C), respectively. However, all three production curves (Figure 8) track very similarly. Thus, it is beyond experimental certainty to distinguish any effects caused by the various preheats for the 7.7 wt.% tar sand.

Permeability Screening

Three experiments (SDA 012, 013, and 015) were conducted on tar sand packed to saturated air permeabilities of 0.07, 0.33, and 0.23 darcies (0.07, 0.33, 0.23 μm^2), respectively. These packed tubes also had initial oil saturations of 68, 61, and 66% PV.

Steam injection was not attained for the two experiments using packed tubes containing oil saturations greater than 66% PV and saturated air permeabilities less than 0.23 darcy (0.23 μm^2). Although the preheat temperature was increased to 560°F (293°C), which further reduced the viscosity but also increased the bitumen swelling, steam injection was not possible at a flowrate of 8.5 cc/min (1.1 lbs/hr) under the 1000 psig (6900 kPa) equipment design limit.

Future simulations are being guided by the results of these screening experiments.

Product Analysis

Simulated distillation is used to determine any change in the recovery mechanism(s) as the steam drive progresses. The composition of the samples as determined by simulated distillation is related to the weight percent of material distilling in three boiling point ranges. The boiling point ranges for the fractions are 300-600°F (149-316°C), 600-1000°F (316-538°C), and greater than 1000°F (538°C).

A difference in the composition is noted for the residual bitumen samples obtained from the top, middle, and bottom of the post-experimental tar sand pack. This compositional change is a gradual increase in the weight percent of material in the middle boiling fraction and a decrease in the percent of material in the residue fraction with increasing depth in the tube. Remember that steam is injected into the top of the tube. The percentage in the middle boiling fraction increased from an average of 25% at the top of the tube to an average of 36% at the bottom of the tube, while the percentage of residue distilling at temperatures greater than 1000°F (538°C) ranges from 72% at the top of the tube to 60% at the bottom of the tube. The composition of the original bitumen is comparable to that obtained from the bottom of the tube. This indicates that the more distillable components are preferentially mobilized from the top to the bottom of the tube and eventually produced with the recovered oil.

This mobilization (steam distillation) of the lower boiling components is reflected in the composition of the recovered oil samples obtained from the 300°F (149°C) preheat experiments (SDA 006, 008, 010/011, 013, and 018). In general, the composition of the recovered oil changes as the steam drive progresses. The weight percent of distillable material increases from about 40% for the original bitumen and a majority of the produced oil to a high of about 55% for the later samples analyzed from SDA 018. This indicates, for these experiments, that primary oil production results from those mechanisms characteristic of a hot water flood (viscosity reduction and thermal expansion). However, as the process continues and steam breakthrough occurs additional oil is produced by those mechanisms unique to a steam flood (steam distillation, solvent extraction, and gas drive). Still to be investigated are those samples obtained from the higher preheat experiments.

Process Efficiency

A key measure for commercial development is the steamflood process efficiency. This process efficiency is typically described by the steam-oil ratio (SOR) which is the volume of water equivalent steam injected versus the barrels of oil recovered. Kuuskraa et al.[(10)] survey of successful steam drive projects indicates the economic success of a steam drive typically requires an SOR of 4-6 and a recovery range of 30-60 percent of the remaining oil-in-place (ROIP). Twenty-six field scale and pilot (20 acres or less) projects are included in this survey. Although the bulk of these steam drives have been in shallow, heavy oil sandstone reservoirs, particularly in California, several recent projects have extended the process to deeper environments, carbonate reservoirs, light oils, and to tar sands (viscosity exceeding 10,000 cp). One Texas tar sand pilot (Conoco's Street Ranch) was completed with an SOR of 11 and an actual recovery of 54% ROIP based on the injection of nearly 3 PV of steam. Conoco's second pilot, from the neighboring Saner Ranch, operated with a much higher recovery efficiency which resulted in a final SOR of 8. However, because of the high capital costs and the production of a high sulfur, low H/C ratio, and low API gravity tar, commercial development of this resource seems very distant[11].

The cumulative steam-oil ratios for the adiabatic boundary, one-dimensional steamfloods within the Asphalt Ridge tar sand are shown in Figure 14. These SOR are averaged according to the tar sand grade and are plotted versus the average cumulative oil recovery at each pore volume of injected steam (refer to Figure 6). The SOR range from 15-30 for the 11.4 wt.% bitumen tar sand at oil recoveries of 10-35% OOIP. The leaner grade, 7.4-7.7 wt.%, tar sand has an SOR which ranges from 22-54 for the identical oil recoveries. Based on the conventional measure for steamflood performance, the economics within this oil-wet Utah tar sand are poor to marginal at best. Further investigations of the steamflood process enhanced by reverse combustion, air co-injection, and other additives are being conducted. In addition, large-scale, sophisticated simulations and numerical modeling are planned for a more thorough evaluation of this process as related to Asphalt Ridge tar sand.

CONCLUSIONS

The following conclusions are relevant to laboratory steam displacement within tar sands from Asphalt Ridge, Utah.

1. Increasing the initial preheat temperature yields an increased rate of oil recovery prior to steam breakthrough.

2. Seven-pore volumes of steam are required to produce 35% OOIP from a previously heated tar sand pack. This translates into a steam-oil ratio of 30. Since commercially successful steamfloods have a steam-oil ratio of 4 to 6, pure steamflooding of these tar sands does not appear economically attractive.

3. After the establishment of a heated flow path and assuming similar sweep efficiencies, oil recovery is increased for richer grades of tar sand because the reducible oil saturation is independent of the initial oil saturation.

4. The reducible oil saturation is dependent on temperature, therefore, increasing temperature (maximize steam pressure) will increase oil recovery.

5. With an established heated flow path (preheat), thermal swelling and viscosity reduction of the bitumen is responsible for production prior to steam breakthrough.

6. Thermal swelling of the bitumen into the gas pore space further reduces the permeability and requires increased injection pressures, prior to steam breakthrough.

7. The steam displacement mechanisms of thermal expansion, viscosity reduction, steam distillation, and solvent extraction have been

detected by simulated distillation. All of these mechanisms contribute to the production of oil from 300°F (149°C) preheated tar sand packs.

8. The post steamflooded saturated air permeability typically is enhanced 30 - 70% above the initial permeability of the tar sand pack.

9. An automated tube packing device has been developed which can consistently produce laboratory packed tubes closely simulating tar sand reservoir properties.

10. Improved thermal recovery laboratory investigations are capable of generating screening criteria supporting future 3-dimensional simulations.

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TABLE I. CORE DATA AND PACKED TUBE RESULTS FOR A UTAH TAR SAND

Source	Deposit	Bitumen Saturation wt.%	Bitumen Saturation % P.V.	Porosity (v. %)	Bulk Density (gms/cc)	Air Permeability (md) Saturated	Air Permeability (md) Extracted
LERC 1C	N.W.A.R.	-	62	26.1	-	132	651
LERC 2C	N.W.A.R.	-	65	31.1	-	85	675
LETC 1S	N.W.A.R.	11.3	78.9	29.5	-	120	2175
Six Random Wells[a]	N.W.A.R.	10.8-11.8	78.8	30.3	2.10	9	758
Tube Packer	A.R. Quarry	11.4	70.2	32.5	2.04	64	-
Seven Random Wells[b]	N.W.A.R.	7-8.5	59.6	28.4	2.08	110	492
Tube Packer	A.R. Quarry	7.7	53	29.7	2.04	440	-

[a] Weighted average from 120 core measurements

[b] Weighted average from 100 core measurements

TABLE 2. PHYSICAL PROPERTIES OF MECHANICALLY PACKED TUBES (ASPHALT RIDGE TAR SAND)

SDA Experiment Number	Initial Oil Saturation			Porosity (v.%)	Bulk Density (gms/cc)	Saturated Air Permeability (darcys)
	wt% bitumen	% PV	OOIP (gms)			
9	7.7	45.7	652	32.9	1.95	1.04
6	7.7	47.7	650	32.0	1.98	1.04
8	7.7	45.5	653	33.0	1.95	.89
10	7.7	48.3	653	31.7	1.99	.94
11[a]	--	--	--	--	--	--
19	7.4	43.8	627	32.9	1.94	1.02
21	7.7	45.6	649	32.9	1.98	.88
20	7.4	46.2	628	31.7	1.98	1.13
18	11.4	61.8	964	35.3	1.96	.50
13	11.4	61.3	942	35.5	1.95	.33
14	11.4	60.9	963	35.6	1.95	.44
12	11.4	68.1	968	33.1	2.02	.07
15	11.4	65.5	969	34.0	2.00	.23
16	11.4	61.3	957	35.5	1.95	.51
17	11.4	64.0	968	34.5	1.98	.55

[a] Same tube as for experiment No. 10

TABLE 3. STEAM DISPLACEMENT EXPERIMENTAL RESULTS FOR ASPHALT RIDGE TAR SAND

SDA Experiment Number[a]	Nominal Preheat Temp. (°F)	Steam Injection Ave. Flowrate (cc/min)	Steam Injection Time (hrs)	Steam Injection Cum. (total pore vols.)	Oil Recovery (% OOIP)	Residual Oil Saturation (% PV)
<u>7.4 and 7.7 wt.% bitumen</u>						
9[b]	215	9.7	32.0	12.9	36.9	28.9
6	300	14.5	28.8	17.9	35.1	30.9
8	325	8.5	41.2	15.2	34.7	29.7
10	325	4.7	43.0	9.0	19.0	--
11[c]	325	9.4	33.8	14.0	18.4	30.2
19	400	7.7	22.2	7.1	30.0	30.7
21	400	7.7	50.0	16.[illegible]	38.8	27.9
20	475	7.7	21.0	7.0	34.8	30.1
<u>11.4 wt.% bitumen</u>						
18	300	7.9	58.3	18.1	49.7	31.1
13	325	8.0	66.8	20.9	48.1	31.8
14	325	4.5, 6.7, 8.5	75.8	17.5	36.5	38.6
12[d]	310 - 560	8.5	15.2	N.A.	N.A.	N.A.
15[d]	400	8.5	1.3	N.A.	N.A.	N.A.
16	400	7.8	40.1	12.3	48.4	31.6
17	475	8.2	34.6	11.5	39.4	38.8

a Adiabatic control for experiment No. 9 and 16-21; isothermal control for the remainder.

b From 32-37.8 hours, increased steam temperature to 700°F. Final total oil recovery is 53.7% OOIP after 15.4 pore vols. and S_{or} is 21.2% PV.

c Total oil recovery for tube used in experiment No. 10 and 11 is 37.4% OOIP.

d Steam injection not achieved.

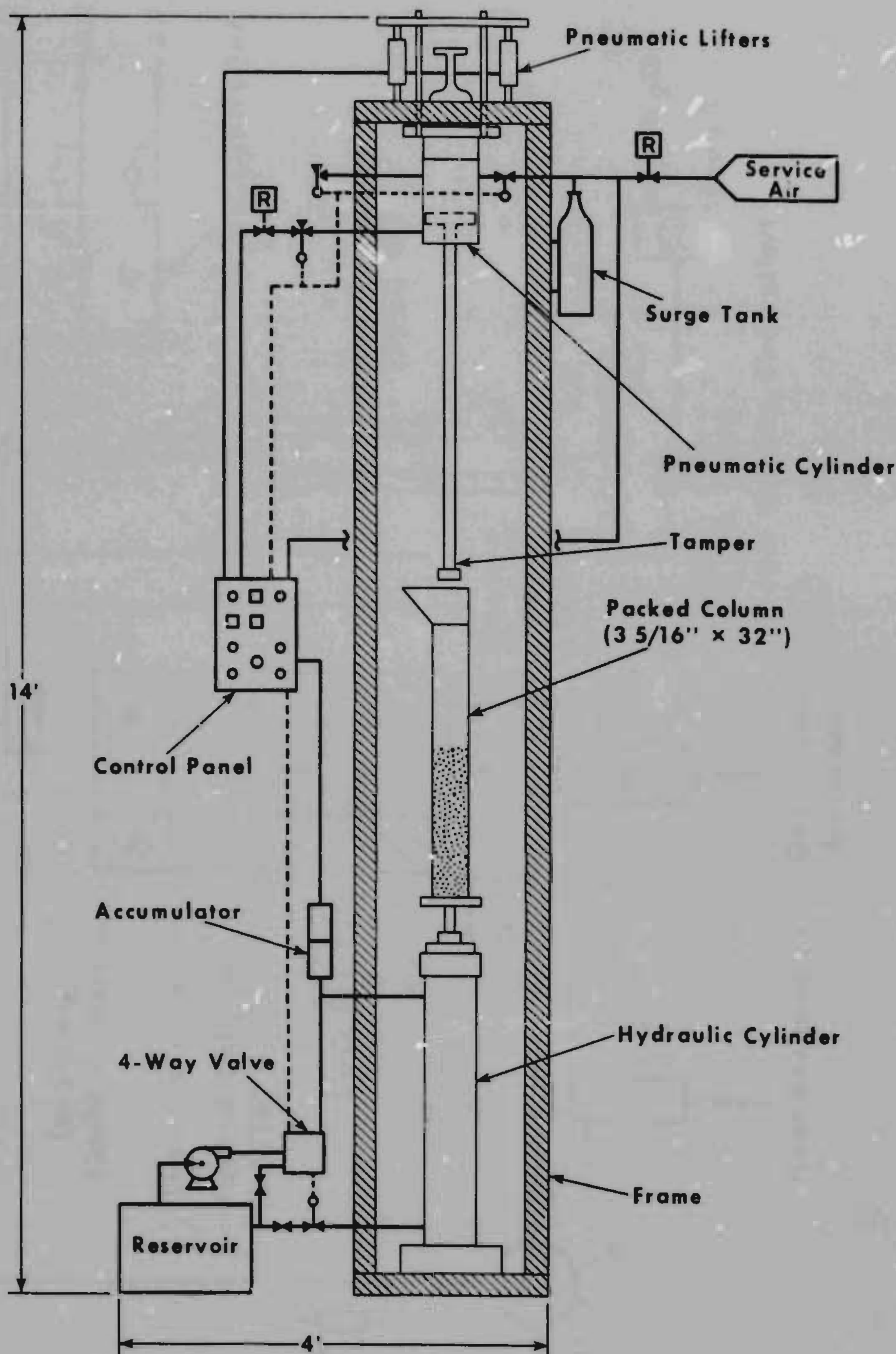

Figure 1. Automated Tube Packing Device

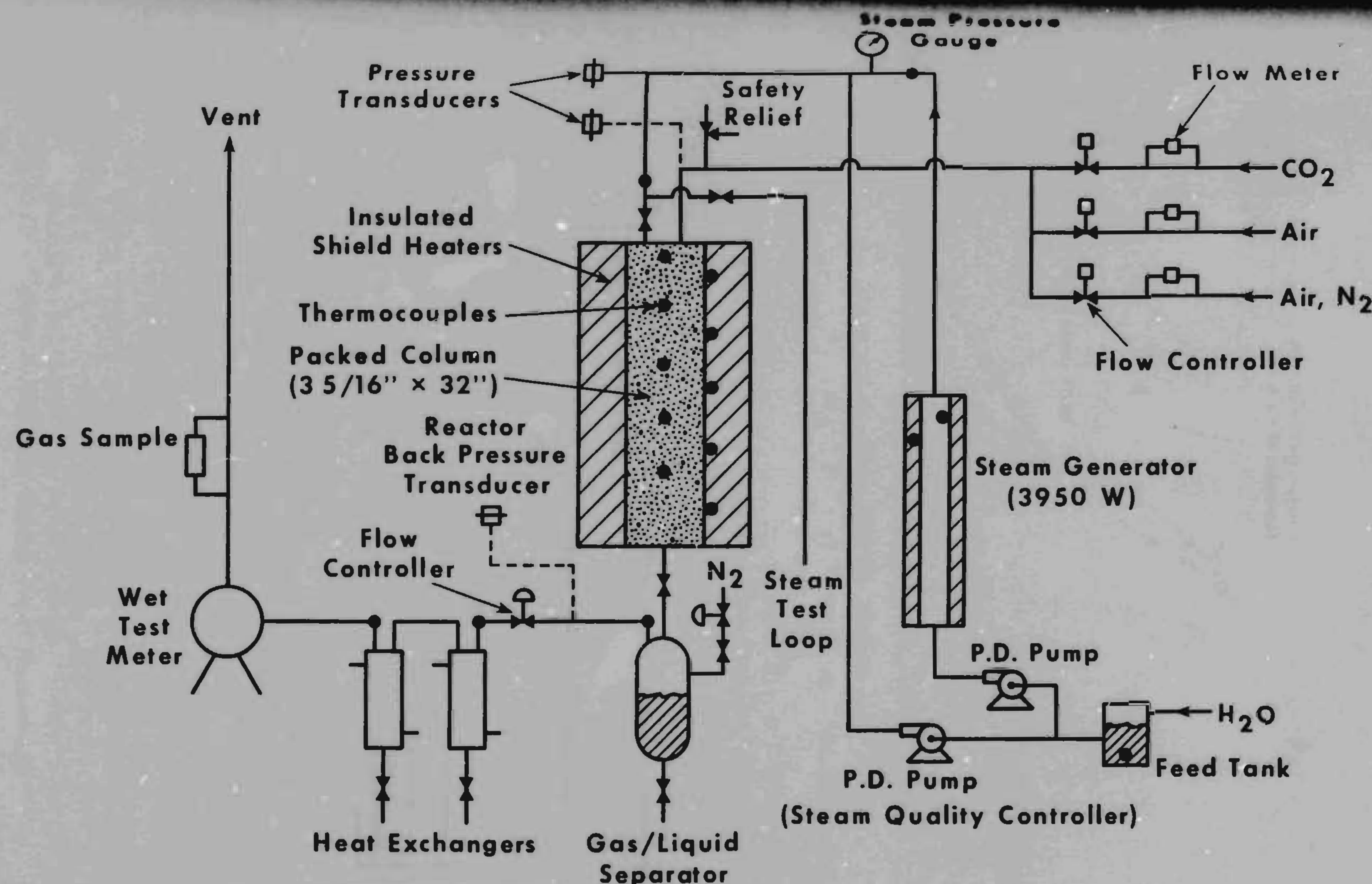

Figure 2. Flow Diagram of a Tubular Combustion/Steam Flooding Apparatus

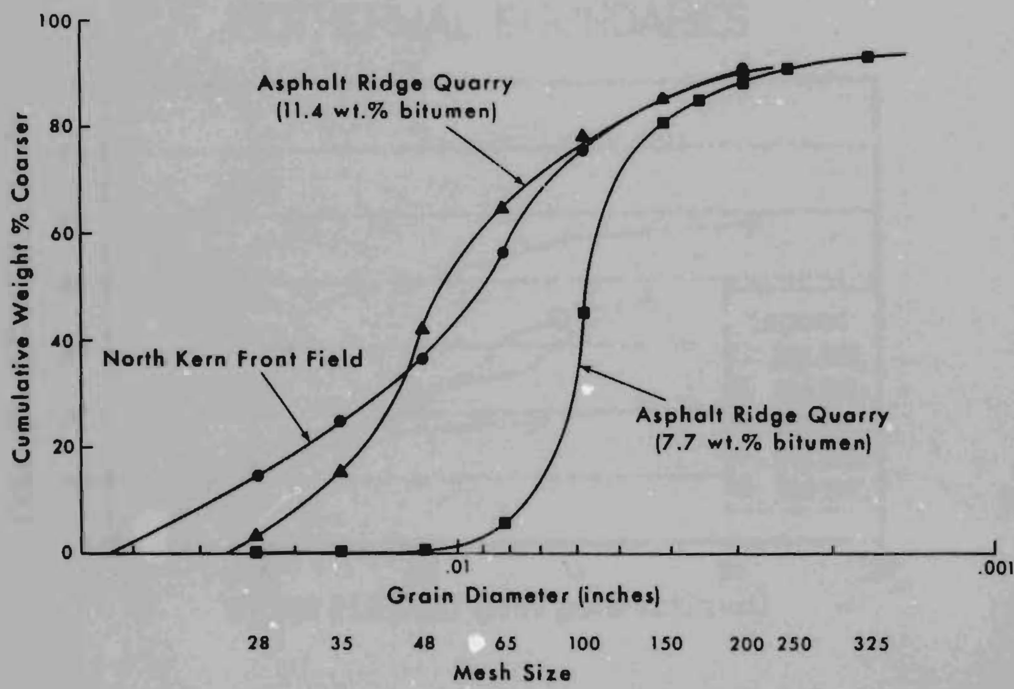

Figure 3. Cumulative Grain Size Distributions

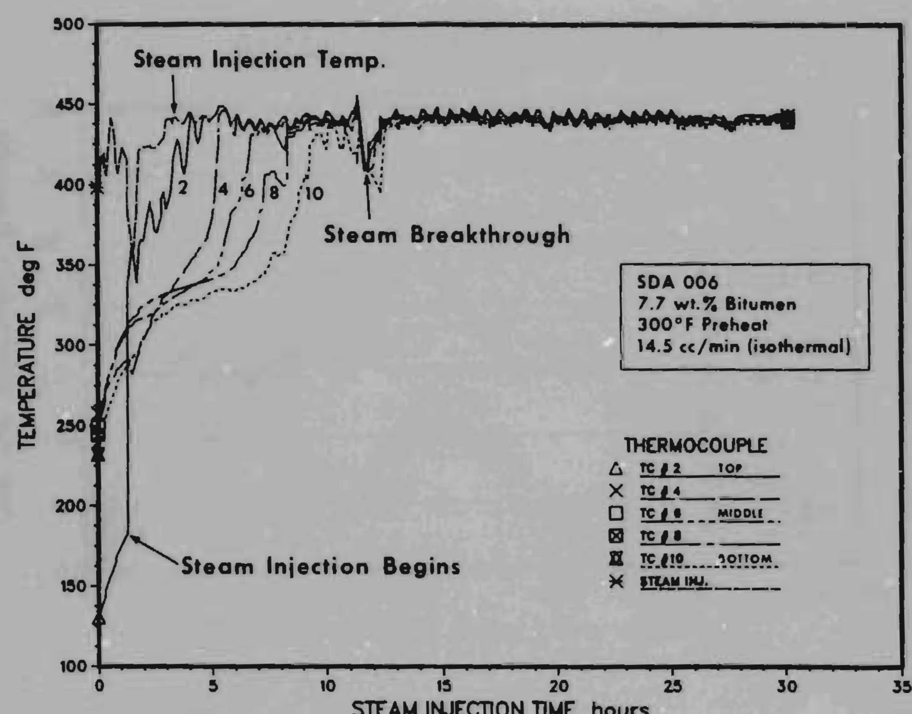

Figure 4. Thermal Steam Front Movement

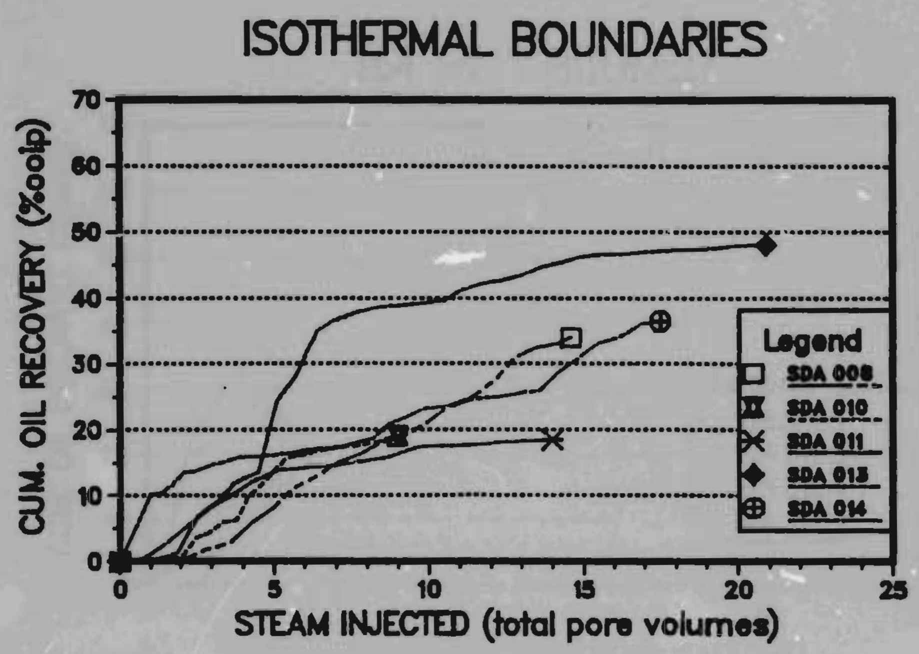

Figure 5. Oil Recoveries for Isothermal Steamfloods

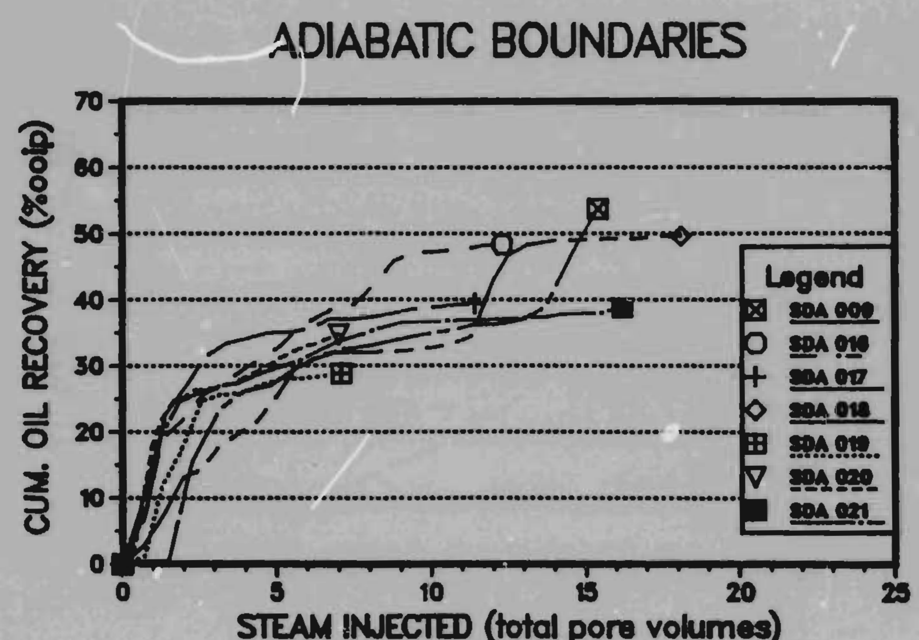

Figure 6. Oil Recoveries for Adiabatic Steamfloods

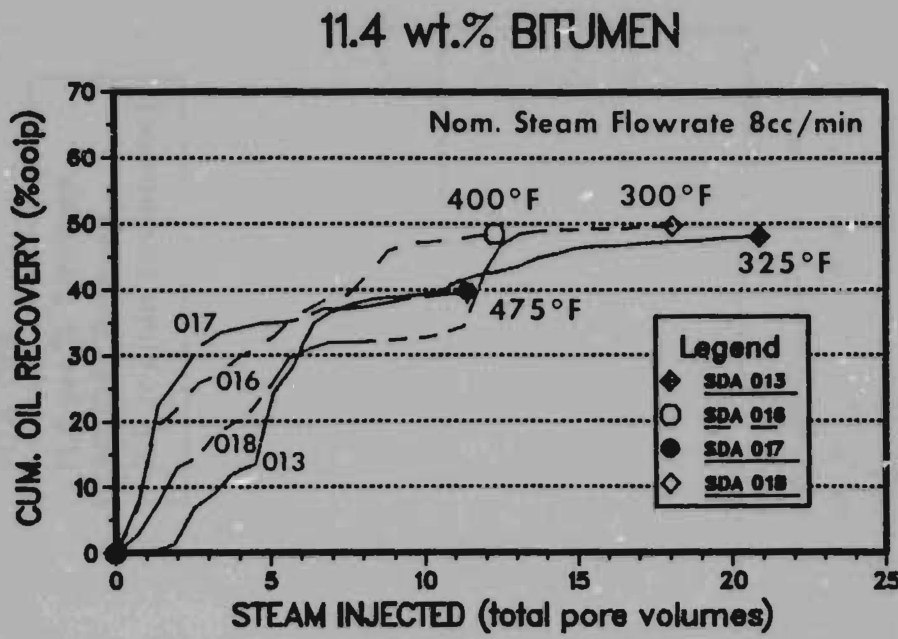

Figure 7. Steamflood Oil Recovery Within a Rich Tar Sand

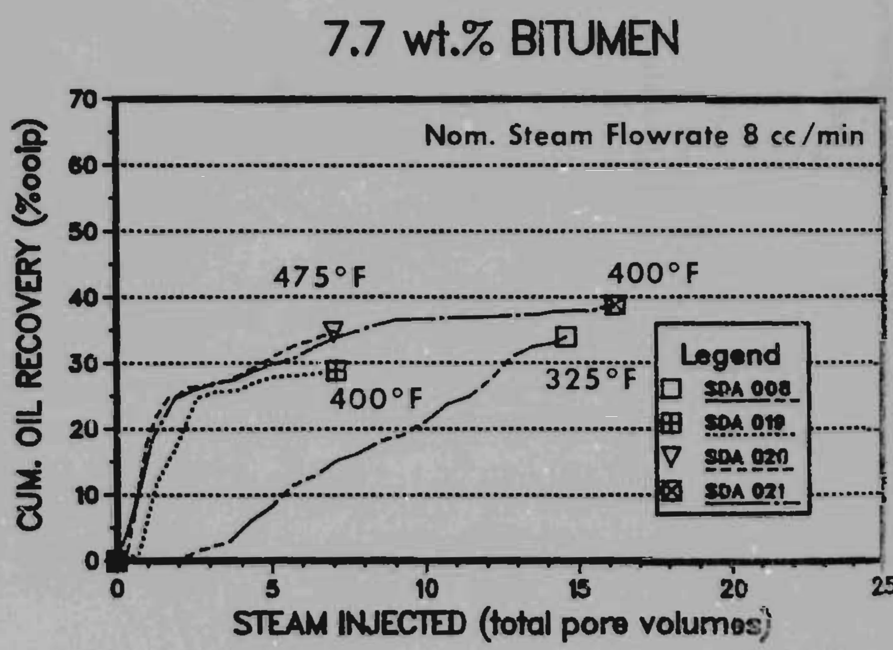

Figure 8. Steamflood Oil Recovery Within a Lean Tar Sand

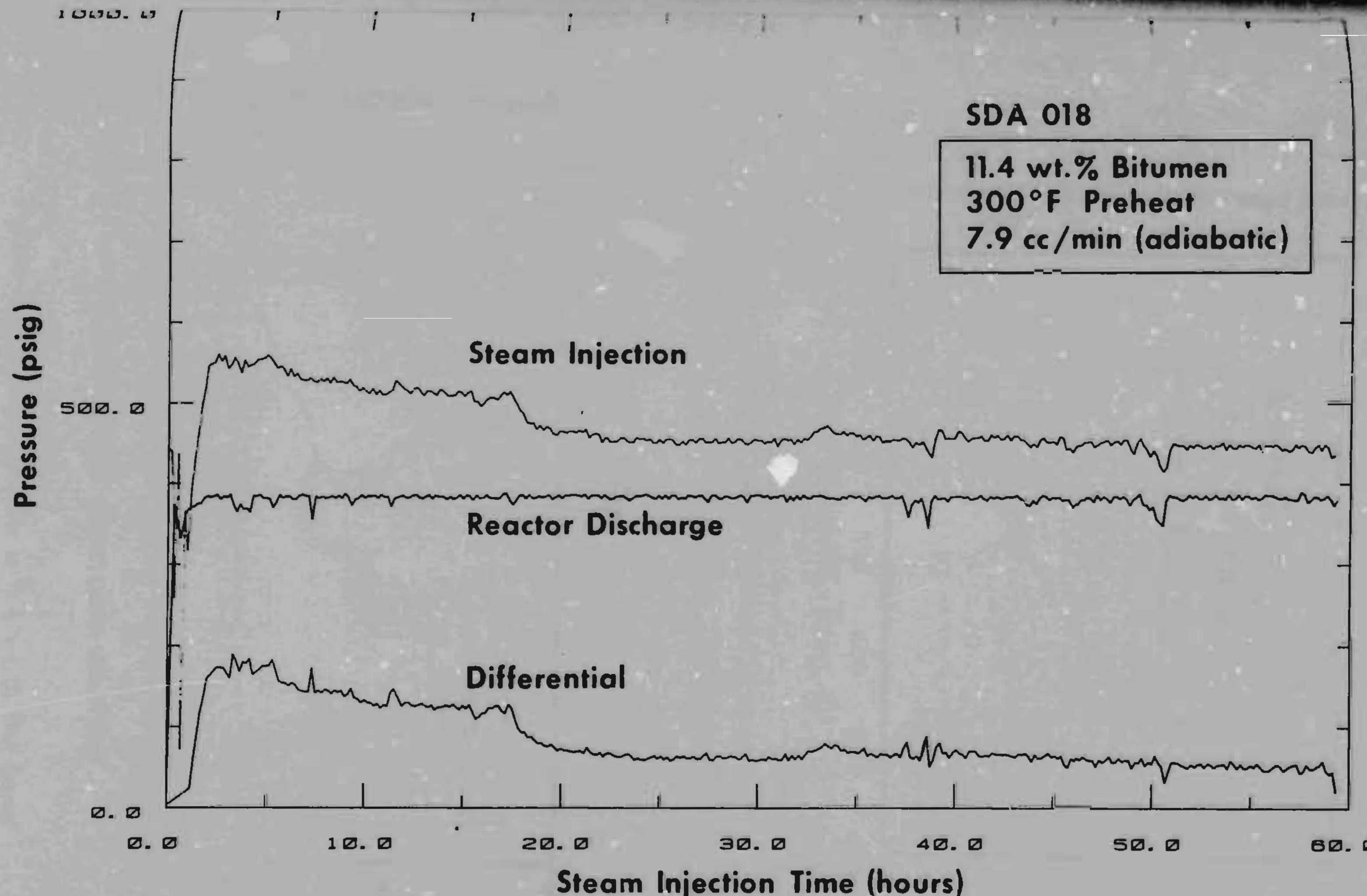

Figure 9. Steamflood Pressure Profile

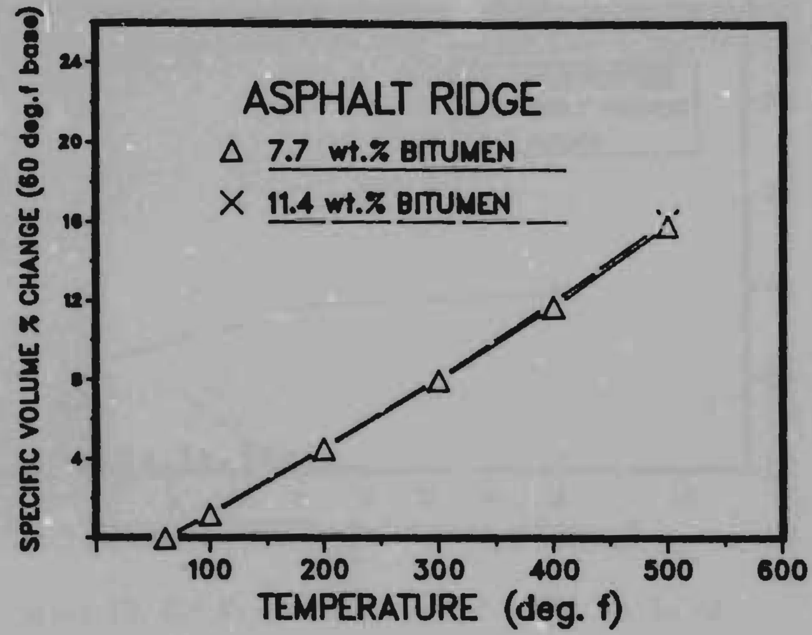

Figure 10. Thermal Volumetric Expansion

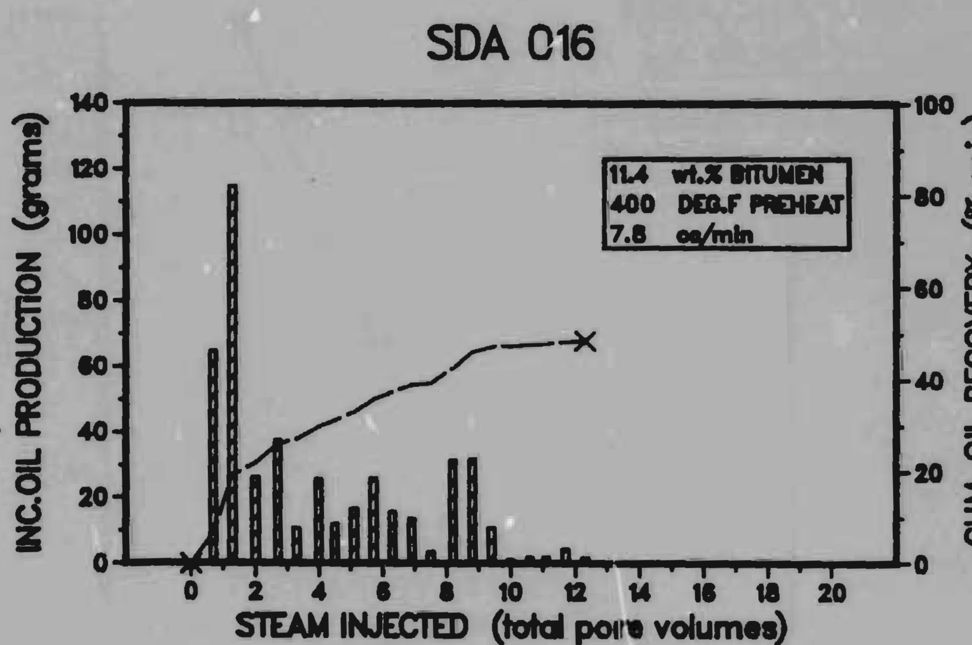

Figure 11. Oil Recovery for a 11.4 wt.% Tar Sand

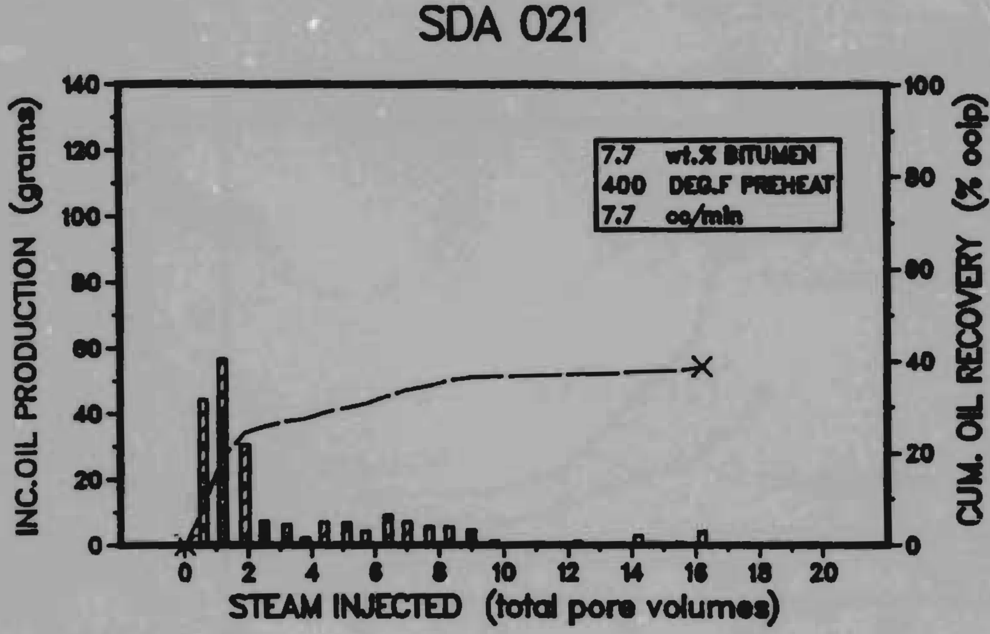

Figure 12. Oil Recovery for a 7.7 wt.% Tar Sand

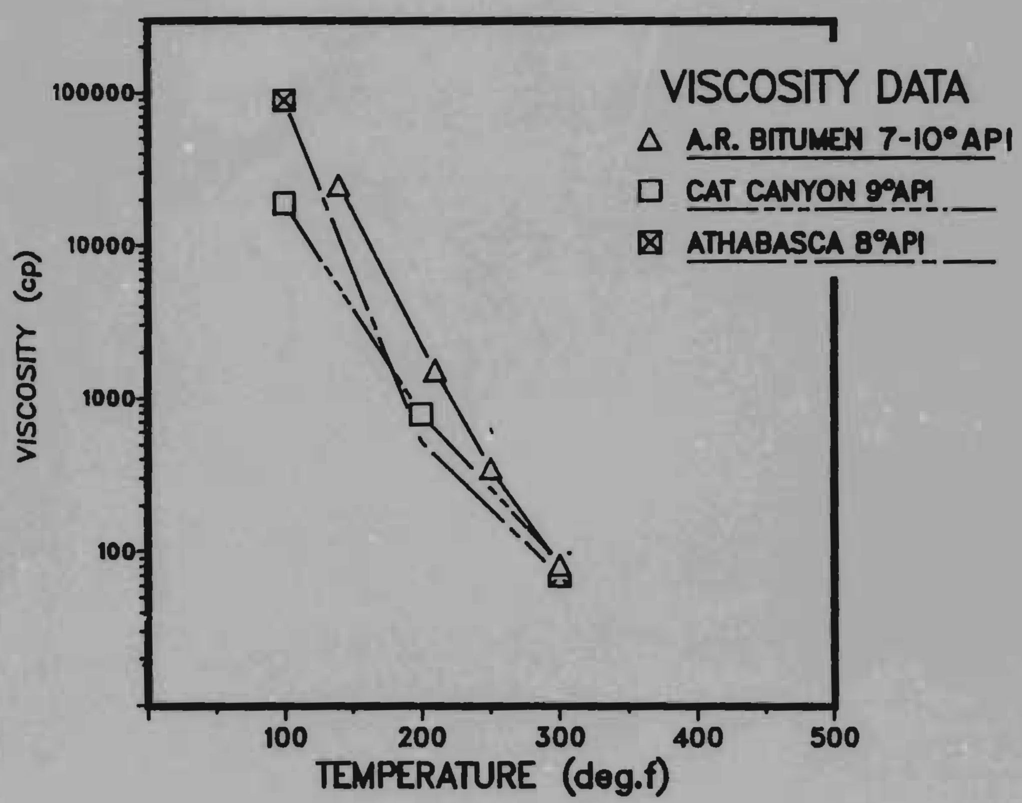

Figure 13. Viscosity Characteristics

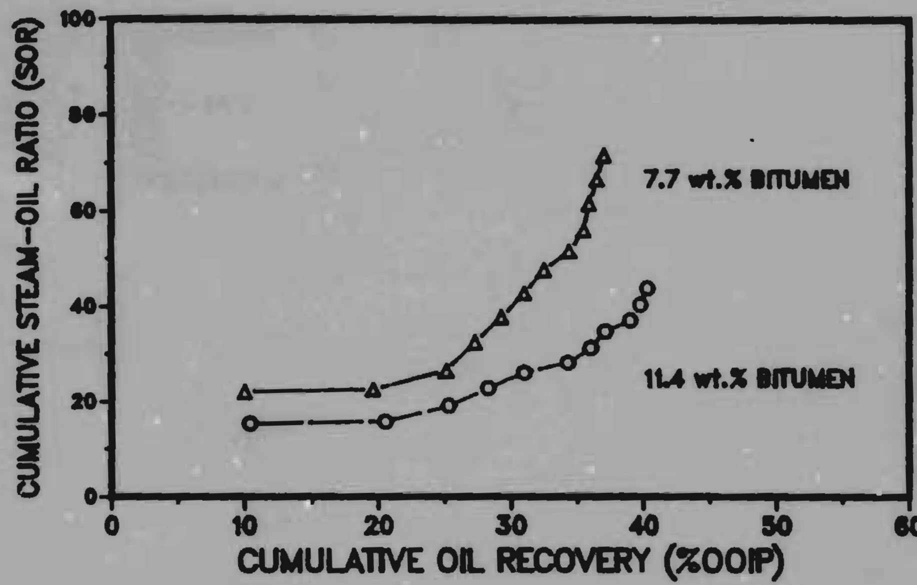

Figure 14. Steamflood Process Efficiency in a Utah Tar Sand

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