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EFFECT OF WETTABILITY ON LIGHT OIL STEAMFLOODING

TOPICAL REPORT

By
David K. Olsen

December 1991

Performed Under Cooperative Agreement No. FC22-83FE60149

IIT Research Institute
National Institute for Petroleum and Energy Research
Bartlesville, Oklahoma

Bartlesville Project Office
U. S. DEPARTMENT OF ENERGY
Bartlesville, Oklahoma

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Prepared for
U. S. Department of Energy
Assistant Secretary for Fossil Energy

Thomas B. Reid, Project Manager
Bartlesville Project Office
P. O. Box 1398
Bartlesville, OK 74005

Prepared by
IIT Research Institute
National Institute for Petroleum and Energy Research
P. O. Box 2128
Bartlesville, OK 74005

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By David K. Olsen

ABSTRACT

This report summarizes NIPER's research on four interrelated topics for Light Oil Steamflooding. Four interrelated topics are described: the methodology for measuring capillary pressure and wettability at elevated temperature, the use of silylating agents to convert water-wet Berea sandstones or unconsolidated quartz sands to oil-wetted surfaces, the evaluation of the thermal and hydrolytic stability of these oil-wet surfaces for possible use in laboratory studies using steam and hot water to recover oil, and the effect of porous media of different wettabilities on oil recovery where the porous media is first waterflooded and then steamflooded.

All elevated temperature capillary pressure evaluations with various fluid/porous media systems yielded similar results. The capillary pressure curves were similar in shape, but irreducible brine saturations were found to increase as run temperatures increased. Wettability values were found to increase (become more water-wet) as run temperatures were increased. Artificially oil-wet porous media were produced by treatment with asphaltenes or polar crude oil components, and by silylation using both liquid-phase and vapor-phase treatments. Thermal stabilities and hydrolytic stability of the oil-wet surfaces were evaluated by observing changes in the wettability index as cores were subjected to hot water or steam displacements, with or without crude oil coating the porous media. Cores treated with asphaltenes or polar crude oil components failed to produce a lasting oil-wet surface. Liquid-phase silylation of silica surfaces yielded oil-wet surfaces that reverted to water-wet upon exposure to hot water. Vapor-phase silylation using bis(dimethylamino)dimethylsilane resulted in a bidentate bound $Si(CH_3)_2$ group chemically bonded to the silica surface. This artificially oil-wet surface was more inert and resisted changes in wettability. Laboratory oil recovery experiments, using steam in one-dimensional Berea sandstone cores of various wettabilities, showed that oil-wet sandstones responded to steam faster than water-wet sandstones, but both attained final residual oil saturations of less than 12%.

A series of steamflood experiments was conducted in a two-dimensional model using water-wet, intermediate-wet, and oil-wet porous media to investigate the steamflood potential for light oil production after waterflooding. The study evaluated the effects of changes in wettability on steamflooding light oils. New London crude oil (32° API) was used in the study. Comparisons of the oil saturation profiles of the sandpacks indicated higher initial oil saturations in oil-wet sandpacks. However, waterflooding recovered less oil at a slower rate and lower oil-water ratio from oil-wet sands. Oil-wet sands showed much higher residual oil saturation after reaching

waterflood residual. Steamfloods initiated at this point displaced little oil from water-wet sandpacks. However, significant oil was displaced from oil-wet sandpacks. This study indicated that final oil saturation after steamflooding is independent of initial wettability.

OBJECTIVE

The purpose of this research was to evaluate specific changes in oil recovery by hot water and steam as a function of changes in wettability of porous media/fluid systems. To conduct this research, methodology was needed to determine changes in capillary pressure and wettability with increasing temperature.

ACKNOWLEDGMENTS

This work was performed by the IIT Research Institute, National Institute For Petroleum and Energy Research (NIPER) and sponsored by the U.S. Department of Energy (DOE) under cooperative agreement DE-FC22-83FE60149. The author wishes to thank P.S. Sarathi, M. E. Crocker, D. Roark, C. Robertson, S. M. Mahmood and E. B. Ramzel, all of NIPER, and J. Betancourt, visiting INTEVEP engineer at NIPER, for their research and analysis, and A. Strycker and M. K. Tham of NIPER and T. B. Reid of the DOE Bartlesville Project Office for their helpful reviews. This report summarizes research conducted as part of project BE11A, Light Oil Steamflooding, and completes milestone 5, FY91. More complete descriptions of this research are given in references.[1-3]

BACKGROUND

Thermal recovery, by cyclic steam and steamdrive, is a commercial oil recovery technology that contributes nearly 454,000 barrels of oil per day (BOPD) or about 6% of the total daily United States oil production.[4] This oil is predominantly heavy oil, 10° to 20° API. Only two light oil steamfloods (LOS) are operating in the United States at the present time and both floods are in DOE-managed Naval Petroleum Reserve (NPR) fields. One flood is being conducted in the Shannon sandstone formation at NPR No. 3, Teapot Dome (WY) field. This test is in a highly fractured, consolidated, tight (63 mD) sandstone at a depth of 325 to 500 ft. The second LOS is in the Shallow Oil Zone (SOZ) at NPR No. 1, Elk Hills (CA) field. The SOZ pilot is being conducted in a highly calcareous, unconsolidated, multisand sandstone at a depth of 2,800 ft. Both steamfloods test LOS technology in very different adverse environments.

One target of LOS research within the last 10 years has been previously waterflooded reservoirs.[5-8] Oil-wet reservoirs may be a more attractive, economic target for LOS because the oil saturation at the beginning of a LOS may be considerably higher in oil-wet reservoirs than in water-wet reservoirs.[9] In strongly water-wet porous media, oil recovery at water breakthrough is high, with little additional production after water breakthrough. In strongly oil-wet porous media, water breakthrough occurs much earlier, and most of the oil recovered is slowly swept out during an extended waterflood with a low oil-water ratio. This parallels what is observed in waterfloods of most sandstone reservoirs. Waterfloods are less efficient in oil-wet reservoirs than in water-wet reservoirs, because more water must be injected to recover the same amount of oil. As the wettability index increases (more water-wet), the water relative permeability increases, and oil relative permeability decreases. Consequently, water flows more easily than oil causing progressively earlier breakthrough and lower oil recovery.[10-11]

NIPER has been investigating the recovery of light oil by steamflooding for several years. Strycker and Sarathi[12] presented a critical review of previous LOS studies. The economics of steamflooding require that the product of oil saturation times permeability be high.[5,13-15] However, most waterfloodable light oil reservoirs have already been waterflooded to a relatively low oil saturation; thus, the porosity-saturation product may be unfavorable, and subsequent steamflooding of such reservoirs may be uneconomic. Injection of steam or any other gas into these previously waterflooded reservoirs would tend to follow previously waterflooded channels and result in poor sweep efficiency. In addition, heat loss to the water phase may be excessive (water has a higher heat capacity than oil). Oil-wet light oil reservoirs, which often exhibit poor waterflood recovery, may have sufficient oil saturation to make light oil steamflooding technically and economically feasible.

NIPER needed porous media that was significantly more oil-wet than very strongly water-wet to evaluate specific changes in oil recovery by treatments with hot water and steam as a function of wettability of porous media/fluid systems. Both strongly oil-wet and intermediate-wet porous media were needed. Several methods were tried to provide these media including precipitation of asphaltene and polar fractions on porous media, treatment of porous media with siloxane and silylating agents in the liquid phase, and finally silylation of the porous media using reagents in the gas phase to attain more uniform coverage of the surface and potentially more stable oil-wet surfaces. The thermal and hydrolytic stability of these oil-wet surfaces needed to be determined to see if the surface was degrading and reverting to a water-wet condition. The surface needed to be sufficiently inert to permit observing the effect of steam on changing the wettability of the surface in laboratory oil displacement tests.

RESULTS AND DISCUSSION

Effect of Temperature on Capillary Pressure and Wettability

The effect of elevated temperature on capillary pressure has been previously studied.[16-19] Samaroo and Guerrero[16] indicated that increases in irreducible water saturation with elevated temperature should correspond with increased oil recovery.

As part of this study, NIPER modified a centrifuge and test cells to evaluate capillary pressure and wettability at elevated temperature.[2] The effect of elevated temperature on core saturation was evaluated in a series of experiments using different porous media-fluid systems including mineral oil and New London crude (32 °API, from the site of a proposed LOS in south-central Arkansas). The results of capillary pressure determinations for a simple porous media-fluid system, nitrogen/brine (2% NaCl)/Berea sandstone at 75°, 150°, 250°, and 350° F are shown in figure 1. The capillary pressure curves were calculated based upon the method of Rajan[20] and show an increase in irreducible water saturation at each temperature at which the centrifuge measurement was conducted. Figure 2 shows the trend of increasing irreducible water saturation for two different fluid systems in Berea sandstone. Both figures show increasing irreducible water saturation with increasing temperature. These results are in agreement with the literature,[16-19] where similar capillary pressure experiments have shown increases in irreducible water saturations with increasing temperature. The increase in irreducible water saturation with increasing temperature has been postulated to arise from a wettability change in the core towards a more water-wet state.[16-19] Another possible cause postulated is a reduction in the oil-water viscosity ratio.[21]

To evaluate the effect of temperature on wettability, a series of experiments was conducted (Fig. 3) with a number of fluid systems in Berea sandstone. The wettability index was calculated using the USBM method.[22] The results show increasing wettability (more water-wet) with increasing temperature. The USBM method uses the ratio of the areas under the imbibition and drainage capillary pressure curves to calculate a wettability index (W), where $W = \log(A_1/A_2)$ and where A_1 and A_2 are areas under the oil and brine-drive capillary pressure curves, respectively. The USBM wettability index typically ranges from -1.0 (highly oil-wet) to +1.0 (highly water-wet) for most reservoir rock. It is possible to exceed these values if the area under one capillary pressure curve is much greater than the other.

Preparation and Evaluation of Artificially Oil-Wet Surfaces

Laboratory studies of fluid displacement in porous media are often used to model oil production occurring in the field. Tests in native-state, preserved cores would be preferred, but this step in the design process is often not feasible because of the high costs of acquiring field core. Outcrop core from numerous areas throughout the world have been used. The literature reveals that very strongly water-wet Berea sandstone is the porous matrix material most often used in the United States for evaluating oil recovery systems designed for sandstone reservoirs. However, oil recovery from Berea sandstone cores is often twice that of native-state cores. The high oil recovery is due to more homogeneous rock than most formations, the low clay content and very

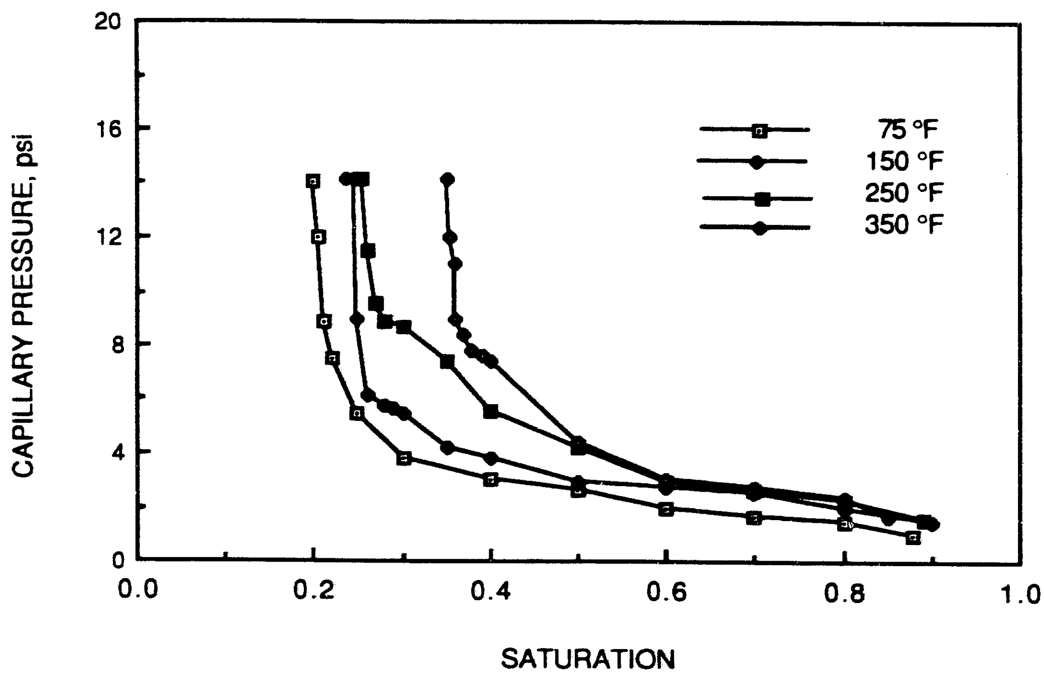

FIGURE 1. - Capillary pressure curves for nitrogen/brine/Berea sandstone.

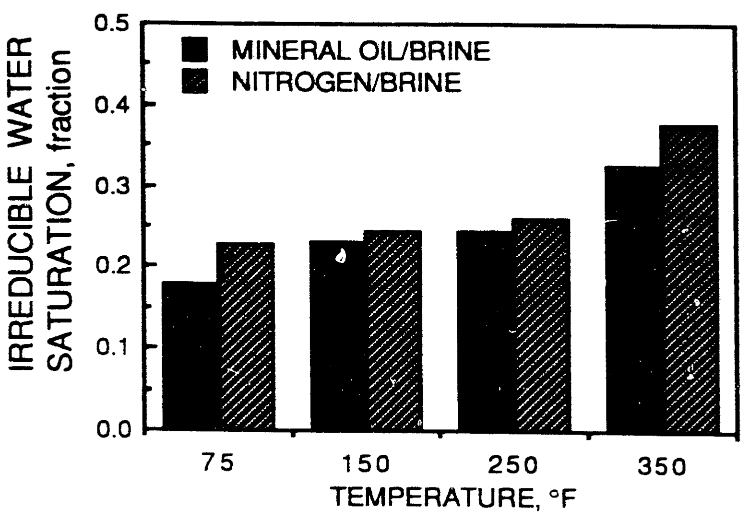

FIGURE 2. - Final irreducible water saturations for nitrogen/brine/Berea sandstone and mineral oil/brine/Berea sandstone.

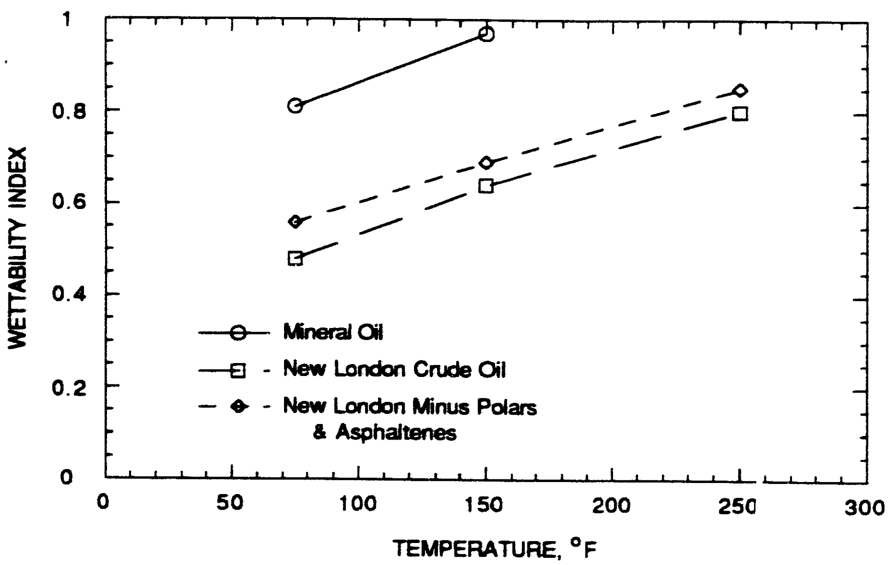

FIGURE 3. - Comparison of wettability values at various temperatures.

strongly water-wet nature of the surface of Berea sandstone. Many oil reservoirs are not very strongly water-wet, but rather are of intermediate wettability.[23-24] The effect of wettability on waterflood oil recovery is well known and has been the subject of recent reviews by Morrow[25] and Anderson.[10-11]

Fired cores are often used to minimize laboratory problems by simplifying operating problems caused by fines migration, ion exchange, adsorption, and clay swelling. Firing cores increases reproducibility of many tests used to evaluate process variables, but this is at the expense of changing other phenomena occurring in the displacement. Each simplification or modification of the porous media tends to remove the modeling of the field away from the native state. Scaled physical experiments often limit the choice of porous media and the wettability of the surface of the media. The importance of porous media selection depends upon what process is modeled, the information needed, and the extent of detail and time that can be expended to scale the oil recovery process.

Physical models are widely used to simulate chemical and physical phenomena in steamflood displacement. In low-pressure, scaled-model studies, the porous media has typically been very strongly water-wet glass beads.[14,26-30] High-pressure models have used unconsolidated field sand of intermediate wettability,[31-32] very strongly water-wet quartz sands,[33-35] or very strongly water-wet consolidated sandstone, such as Berea sandstone,[34-36] or crushed Berea sandstone[36-37] as the porous media in their laboratory studies of thermal oil recovery processes.

In recent years, NIPER has conducted light oil steamflood displacement tests using each of the above porous media, but our capillary pressure/wettability measurements have indicated that oil-wet or intermediate-wet field sands became more water-wet during steamflooding,[2,38]. Crocker and Marchin[39-40] conducted a series of laboratory studies to produce stable wettabilities in core samples using both asphaltenes and polar fractions of crude oils and organosilane agents applied in the liquid phase. They found that the wettability change was not permanent and could be reversed by soaking in brine. Recently, Takach, et al. used gas-phase silylation to obtain an oil-wet surface on glass plates[41] and cores[42] for their study of waterflood and chemical flooding EOR.

Silylation involves chemical modification of the silica surface (replacement of the H-atoms of the surface hydroxyl groups by covalently bound organosilyl groups) to produce a hydrophobic surface and is used extensively in the manufacture of chromatographic column packings to produce a reverse phase or hydrophobic surface. There are several different ways that the Si-O-H functional group on a silica surface can be capped, as shown by the series of reactions in figure 4. The most common method uses a monofunctional silylation agent that forms a single bond, such as with hexamethyldisilazane. Monofunctional endcapping gives a very reproducible surface and controlled coverage. Polyfunctional silylation agents can form multiple bonds to the silica surface such as obtainable with dichlorodimethylsilane or bis(dimethylamino)dimethylsilane which form bidentate molecules covering the surface.

NIPER prepared cores, plugs, and unconsolidated sand used for oil-wet displacement tests or wettability measurements by two different techniques: liquid-phase and vapor-phase silylation. The liquid phase procedure has been described[1] using either of two silylating agents, trioctylchlorosilane $(C_8H_{17})_3$ Si Cl or dimethyldichlorosilane$(CH_3)_2Cl_2Si$ in toluene. Vapor-phase silylation of silica surfaces has been used to convert water-wet glassware used in analytical laboratories to a hydrophobic surface or for making hydrophobic packings for high-performance liquid chromatography.[43] Vapor-phase laboratory silylation with bis(dimethylamino)dimethylsilane, $[(CH_3)_2N]_2Si(CH_3)_2$ or hexamethyldisilazane, $[(CH_3)_3Si]_2NH$ were used to prepare oil-wet porous media.[1,41-42]

Several tests were conducted to evaluate the thermal and hydrolytic stability of porous materials prepared by liquid or gas-phase silylation and of surfaces treated with crude oil fractions precipitated on the surface. The stability of the surface coating was evaluated by measuring the wettability of plugs using the USBM method with mineral oil (table 1) or New London crude oil as the wetting phase (tables 2 and 3). The use of crude oil fractions (asphaltene or polar fractions) from a number of crude oils, dispersed in mineral oil allowed the preparation of less water-wet surfaces and tended toward intermediate-wettability. However, the surface lost its intermediate-wettability upon flushing with crude oil (100 PV) or extensive waterflooding (>100PV).

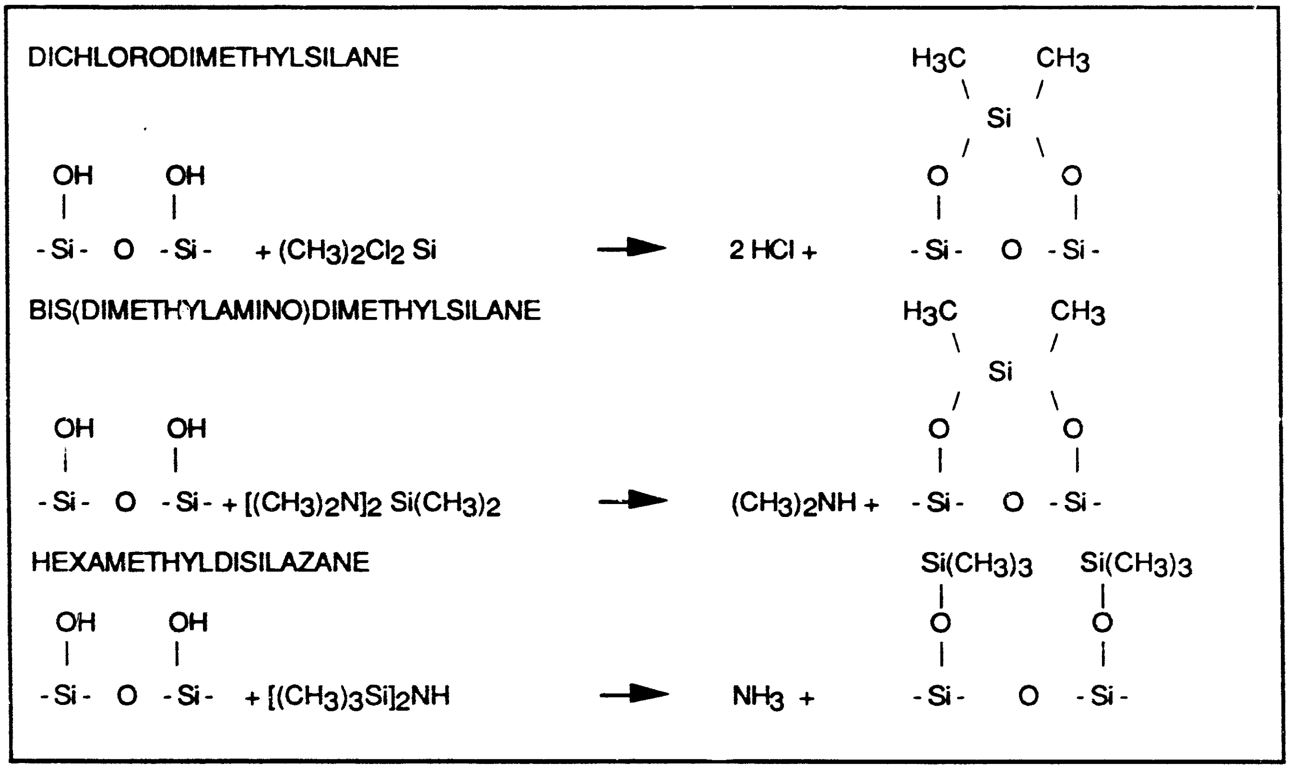

FIGURE 4. - Schematic of chemically bound organo silanes on silica surface.

TABLE 1. - Wettability changes of Berea sandstone with crude oil fractions

Wettability of Berea core with mineral oil	Source of Oil (Formation, State)	Wettability of Berea core with mineral oil/ asphaltenes	Wettability of Berea core with mineral oil/ polars
+0.81	Stevens, CA	+0.21	-0.06
+0.81	Anadarko, OK	+0.38	+0.25
+0.81	Woodbine, TX	+0.35	+0.21

TABLE 2. - Changes in wettability of silylated Berea sandstone and Quartz sands

Silylation treatment	None	Liquid-Phase $Si(C_8H_{17})_3$	Liquid-Phase $Si(CH_3)_3$	Vapor-Phase Bidentate $Si(CH_3)_2$
Untreated (Berea Sandstone)	+0.48[1]			
Silylated (Initial)		-0.82[2]	-0.78[1]	-0.66[3]
After 48 hr at water reflux	+0.51[3]	+0.32[3]	+0.47[3]	-0.45[3]
After 8 hr steam from 285° to 335° F				-0.29[3]
After 8 hr steam from 335° to 365° F				+0.09[3]
1-D steamflood at 350° steam injection end of oil saturated core after 10 hrs of steaming				-0.42
1-D steamflood at 350° production end of oil saturated core after 10 hrs of steaming				-0.52
Untreated Quartz sand	+0.53[3]			
Silylated Quartz sand (Initial)				-0.39[3]
After 8 hr steam from 335° to 365° F				-0.21[3]

[1] Average of 3 tests. [2] Average of 2 tests. [3] Average of 6 tests.

TABLE 3. - Wettability increase with temperature for various systems.

	75° F O/W	75° F W/W	150° F O/W	150° F W/W	250° F O/W	250° F W/W
Wettabilities of consolidated Berea sandstone cores						
Brine/mineral oil	-0.51	+0.75	-0.30	+0.92		
Brine/New London	-0.66	+0.40	-0.47	+0.78	-0.14	+0.95
Wettabilities of unconsolidated quartz sand						
Brine/New London	-0.39	+0.53	-0.21	+0.75	+0.27	+1.06
Wettabilities of unconsolidated Berea sandstone cores						
Unextracted New London crude	-0.45	+0.52	-0.15	+0.85	+0.03	
		+0.18				+0.81
Brine/mineral oil		+0.60		+0.87		+1.21

A comparison of the porous media prepared by the two silylation techniques is shown in table 2, where New London crude oil/1% NaCl solution was used in the centrifuge method for determining wettability. Unsilylated Berea sandstone was water-wet (+0.48). The surfaces produced by liquid-phase silylation, giving bonded $Si(CH_3)_3$ and $Si(C_8H_{17})_3$ groups, and vapor-phase silylation with bis(dimethylamino)dimethylsilane producing a bidentate bonding of $Si(CH_3)_2$ to the silica surface, produced oil-wet surfaces whose wettability indices were -0.82, -0.78, and -0.66, respectively. Selected plugs were refluxed in water in a Dean Stark extractor at atmospheric pressure. Untreated Berea sandstone increased in wettability to +0.51, and both sets of plugs prepared by liquid-phase silylation reverted to a more water-wet condition, +0.32 and +0.47, respectively. Only the plugs prepared by vapor-phase silylation with bis(dimethylamino)-dimethylsilane remained oil-wet, -0.45. The bidentate bonded silylated cores were then subjected to more severe temperature and hydrolysis conditions. They were mounted in Hassler sleeves and subjected to steam injection (two different steam temperature conditions) for 8 hours. More than 100 PV of cold water equivalent steam was injected in each experiment. This resulted in decreasing the oil wettability and a shift to intermediate-wettability, -0.29 and +0.09. Wettability analysis was also conducted on plugs obtained after 10 hours of steamflooding oil-saturated cores. Plugs from the injection and production ends of a 1-D steamflood showed some decrease in oil wettability, but the surface of the core still remained oil-wet, -0.42 and -0.52. There was almost a direct correlation between the severity of the steam treatment and the increase in water-wetness in these experiments. Saturation with crude oil reduced the rate of change in wettability. Silylated cores steamed at higher temperatures or with more pore volumes of steam or longer time periods became more water-wet. Silylated porous media prepared with bis(dimethylamino)dimethylsilane have been used in NIPER laboratories for hot water floods in the presence of crude and refined oils at 190° F (hot waterfloods where <4 PV of hot water was injected) without any detectable change in wettability.

A series of experiments was conducted on very strongly water-wet Berea sandstone or quartz sand and on oil-wet Berea sandstone or quartz sand, prepared by vapor-phase silylation with bis(dimethylamino)dimethylsilane (table 3) to confirm the effect of temperature on wettability. In each system, the wettability index increased (became more water-wet). At 250° F, the initially water-wet porous media has a USBM wettability index greater than one. This is due to the area under one capillary pressure curve being much greater than the other.

Steamflood Performance of Water-Wet, Intermediate-Wet and Oil-Wet Porous Media

Laboratory waterfloods of water-wet systems behave very differently from those of oil-wet systems. In strongly water-wet porous media, oil recovery at water breakthrough is high, with little additional oil production after water breakthrough. In strongly oil-wet porous media, water breakthrough occurs much earlier, and most of the oil recovered is slowly displaced during an extended waterflood with a low oil/water ratio. This parallels what is observed in waterfloods of most sandstone reservoirs; waterfloods are less efficient in oil-wet reservoirs than in water-wet reservoirs because more water must be injected to recover the same amount of oil. As porous media becomes more oil-wet, the water relative permeability increases, and the oil relative permeability decreases. Water flows more easily than oil causing progressively earlier breakthrough and lower economic oil recovery.[11]

A pair of duplicate 1-D steamfloods was conducted with New London crude oil, using fired strongly water-wet Berea sandstone cores and oil-wet cores obtained from vapor-phase silylation using bis(dimethylamino)dimethyl silane. These 1.5 in. x 28 in. cores were vacuum water saturated, flooded with >25 PV of 1% NaCl brine, and then oil saturated with New London crude oil. Backpressure on the system was set to 150 psi, and the cores were steamflooded (no preliminary waterflood). The production histories are shown in figure 5. Energy input (steam rate) was maintained as constant as possible for both runs, although the steam injection rate and back pressure were reduced to maintain constant injection pressure. Steam breakthrough occurred about 7 hours into each flood.

Oil-wet cores, because of their preferential affinity for oil, exhibited a higher initial oil saturation and a higher residual oil saturation at the termination of the steamflood than water-wet cores. The slope of the oil production curve during the first part of the steamflood was less steep for a water-wet core than for an oil-wet core because the water-wet core had a higher initial water saturation and a greater percentage of energy was consumed in bringing the connate water to steam temperature. Consequently, less energy was available to heat the oil. The kick in oil production occurred at different times in these experiments. The sudden kick in oil production in the case of the oil-wet core after about 5 hours of steam injection might have resulted from gradual shifting of the wettability of core toward water-wet and banking of the oil. The sudden kick in oil production in the water-wet core which occurred after about 6-1/2 hours of steam injection can be attributed to the decrease in the consumption of energy for bringing in situ water to steam temperature and the availability of more energy for oil production. After steam breakthrough, the water-wet core continued to produce greater amounts of oil because of a lower affinity for oil as compared to the oil-wet core.

Light Oil Steamflood Displacements in 2-D Sandpacks

Most light oil reservoirs are waterflooded after primary production. To investigate the steamflood oil recovery potential after waterflooding, a series of experiments was conducted in a

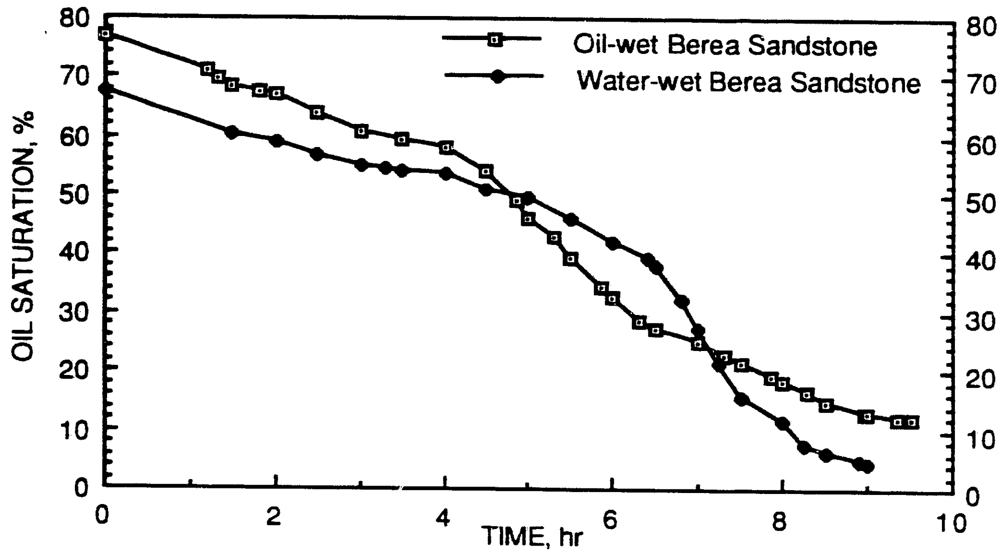

FIGURE 5. - Oil production from steamflooding oil-wet and water-wet Berea sandstone in a 1-D model.

2-D sandpack packed with quartz sands of various wettabilities. The experiments incorporated strongly oil-wet porous media (silylated quartz sand prepared from vapor-phase silylation with bis(dimethylamino)dimethyl silane), quartz sand that had been silylated to yield a surface of intermediate wettability, and untreated very strongly water-wet quartz sand. The effects of wettability are illustrated by the oil production and decline curves in figures 6 through 9. The oil-wet quartz sand yielded a high initial and high waterflood residual oil saturation (figs. 6 and 9). Quartz sands of intermediate wettability showed lower initial and intermediate waterflood residual oil saturation, but they were steamflooded to a low residual oil saturation (figs. 7 and 9). Water-wet quartz sand resulted in the lowest initial oil saturation, the lowest oil saturation after waterflood, and the lowest oil production by steamflooding (figs. 8 and 9). In each experiment, waterfloods were conducted until the water cut was greater than 97% before the start of steam injection. In the case of the oil-wet sand, the oil saturation continued to drop as steam was injected and the water, sand, and oil were heated. The oil-water ratio abruptly increased just before steam breakthrough in the cases of intermediate and oil-wet sands. During the steamflood, the most significant oil production was seen in those sandpacks which were more oil-wet. When compared with intermediate wet sands, the oil saturation decline curve for the oil-wet sands did not decrease as sharply as expected. Comparison of the oil saturation profiles of these sandpacks indicates that waterflooding recovers more oil from sands that are more water-wet. These results from 2-D sandpacks indicate that oil recovery by steamflooding of oil-wet sands looks very promising.

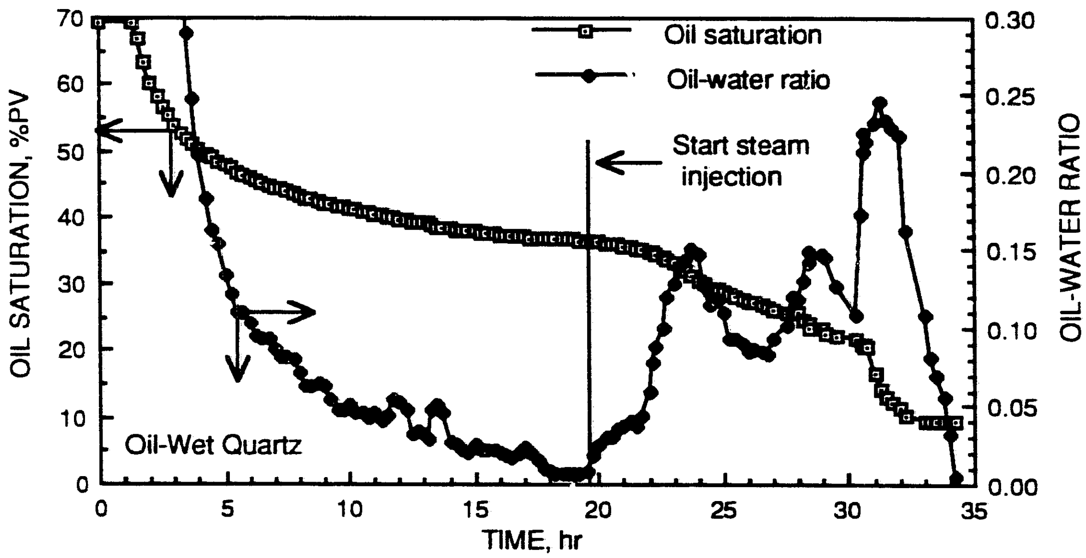

FIGURE 6. - Oil production from a 2-D model packed with strongly oil-wet quartz sand, waterflood followed by steamflood.

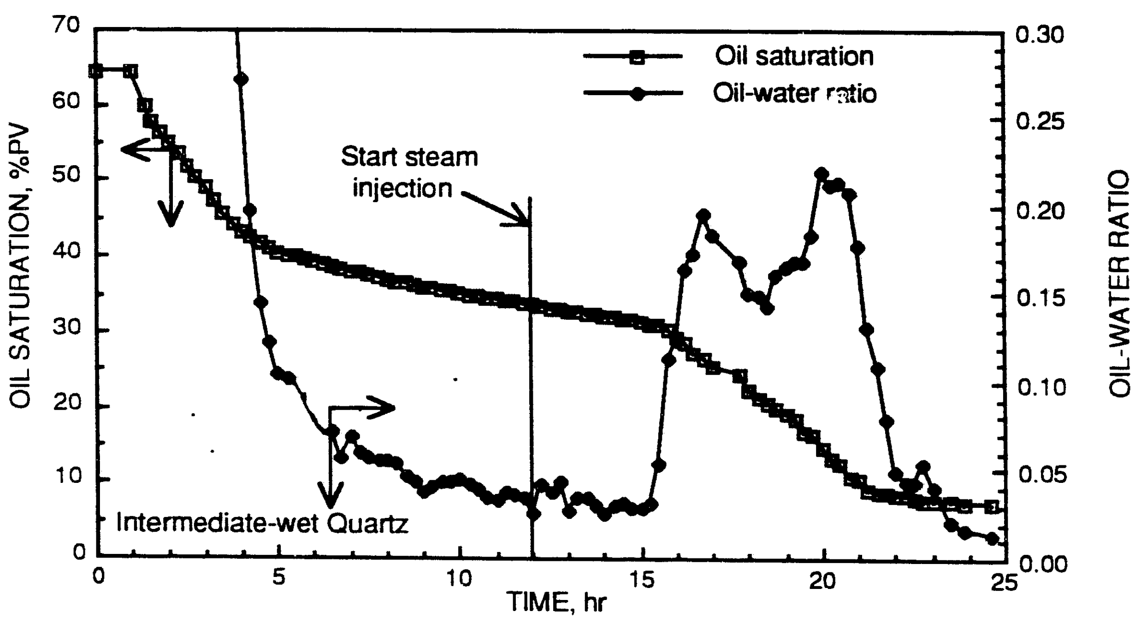

FIGURE 7. - Oil production from a 2-D model packed with intermediate-wet quartz sand, waterflood followed by steamflood.

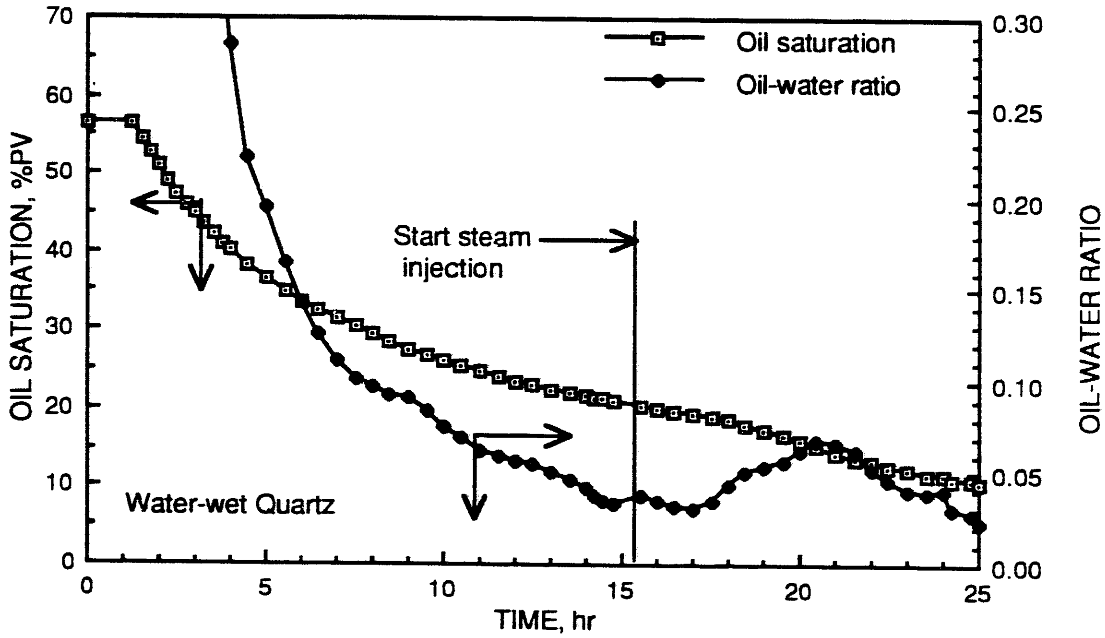

FIGURE 8. - Oil production from a 2-D model packed with water-wet quartz sand, waterflood followed by steamflood.

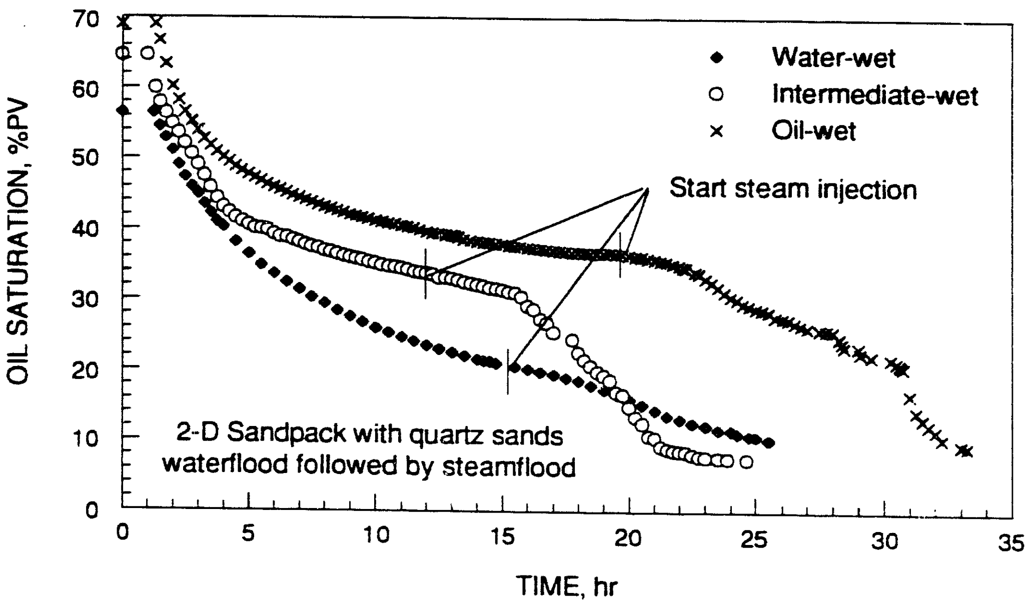

FIGURE 9. - Comparison of oil production from 2-D models, waterflood followed by a steamflood, in oil-wet, intermediate-wet, and water-wet quartz sandpacks.

Economic Target of Light Oil Steamflooding

One of the principal advantages of steamflooding oil-wet light oil reservoirs, in addition to possible high oil saturation, is that the crude oil sells for a light oil price. Heavy oils, such as Kern River California crude, 13° API, sell for only about two-thirds of the price of West Texas Intermediate crude oil, figure 10.[43] Thus, the economics of light oil steamflooding in oil-wet reservoirs that have high oil saturation and have appropriate geology and mineralogy along with high permeability may be attractive.

SUMMARY AND CONCLUSIONS

The use of Berea sandstone as a porous media matrix in preliminary evaluations or screening of oil recovery processes has been widely practiced. This report summarizes the use of silylating agents in both the liquid and the vapor-phase to convert hydrophilic, very strongly water-wet Berea sandstones or unconsolidated quartz sands, to hydrophobic, oil-wetted, surfaces for use in laboratory studies of oil recovery with steam and hot water. The thermal and hydrolytic stability of the oil-wet surfaces were evaluated by measuring changes in the wettability index of cores after they were subjected to hot water or steam, both in the presence and absence of crude oil.

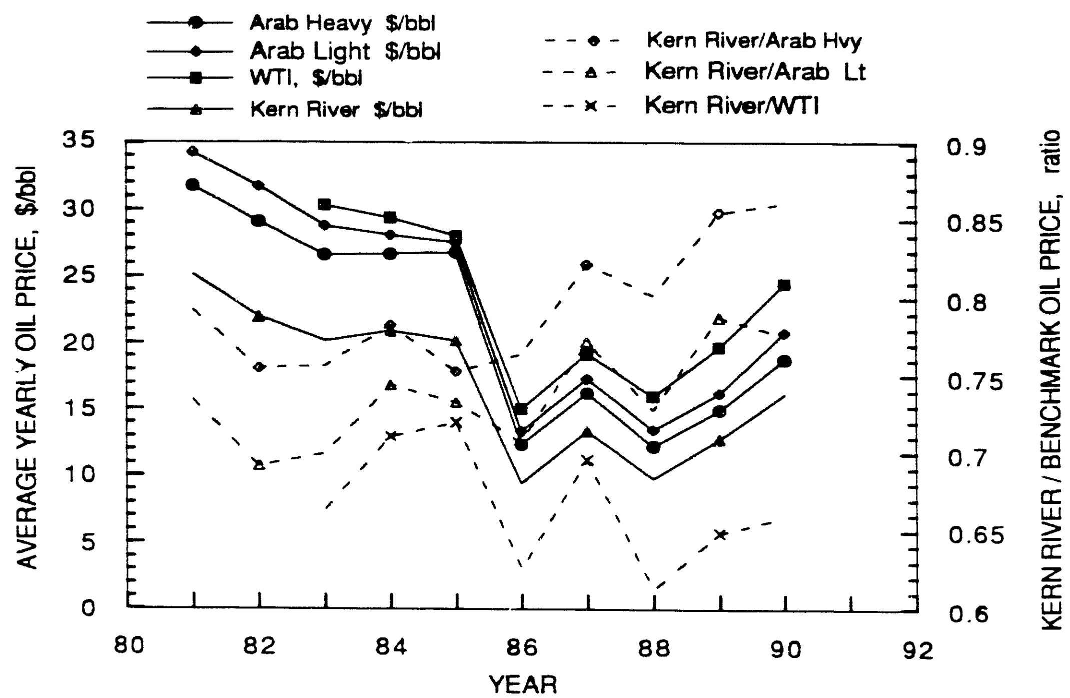

FIGURE 10. - Comparison of average yearly oil price of benchmark crude oils with Kern River 13°API gravity oil.[43]

The vapor-phase silylation process using bis(dimethylamino)dimethylsilane to treat silica surfaces has yielded oil-wet surfaces with more uniform coverage that were more hydrolytically and thermally stable, but they were still transformed to water-wet surfaces upon extended steaming and higher steam temperatures. This process produces an oil-wet surface that is more thermally and hydrolytically stable than previous liquid-phase silylation processes. However, we have not been able to decouple degradation of the silylated surface from any change in surface properties. In the presence of crude oil, the oil-wet surface prepared from vapor-phase silylation using bis(dimethylamino)dimethylsilane to treat silica surface resists changes in wettability under hot water and low temperature steamflood conditions and allows its use in laboratory studies of steam and hot water oil recovery. The stability of the surface is expected to degrade with more severe (higher steamflood temperatures) conditions.

Capillary pressure/wettability measurements indicate that oil-wet or intermediate-wet sands become more water-wet with increasing temperature and that the irreducible water saturation increases as the temperature increases.

Oil production and oil saturation profiles from 2-D sandpacks of water-wet, intermediate-wet, and oil-wet porous media, have been compared where a light crude oil is displaced by a waterflood followed by a steamflood. These data indicate that oil-wet sandpacks oil have a higher initial oil saturation and waterflood (to an economic limit) to much higher waterflood residual oil saturation than either intermediate-wet or water-wet sandpacks. Steamfloods initiated at this point displace little oil from water-wet sandpacks and displace increasingly greater amounts of oil from more oil-wet sandpacks. This behavior is anticipated based upon water displacement of oil from porous media of varying wettability. The steamfloods required increasing response times (steamflood rate and injection pressure were maintained as constant as possible in each of the three experiments) to produce an oil kick in the order: oil-wet, intermediate-wet and finally water-wet. The oil-wet system responded the quickest because there was less water in the sandpack. Since water has a higher heat capacity than oil, more energy (steam) was required to heat the system and steam distill the oil from a water-wet system. This study also indicates that final oil saturation, after steamflooding, were nearly independent of initial wettability as oil saturations were 8 to 10 % PV at the conclusion of the steamflood.

Steamflooding light oil, oil-wet reservoirs, may be an attractive economic target in the appropriate geologic setting. In addition to light oil commanding a much higher price than heavy oil, the response time between steam injection and oil production is short, making economic payback more attractive.

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