allow their movements, thus lowering water mobility and increase vertical and sweep efficiency. Because of the interplay of these mechanisms, alkaline flooding is an extremely complex oil recovery process and tends to be site specific in terms of process design. Recognition of the individual mechanisms should allow profitable application of alkaline flooding to a wide range of reservoir types. Since the main significant characteristics of the crude oil of Safaniya field is its high acidity (1.4 mg KOH/gm), this may make Safaniya field a good candidate for successful enhanced recovery by alkaline waterflooding. Therefore, this work was devoted to study the tertiary alkaline flooding process under Safaniya reservoir conditions.

Experimental work

Fluid-rock properties

Fluid and rock properties are important factors in alkaline waterflooding.

A digital tensiometer apparatus was used to determine the transient interfacial tension between Safaniya crude oil and NaOH solution. The instrument was equipped with a temperature control system which adjust temperature within ±0.1. Measurements of the interfacial tension between Safaniya (laboratory and reservoir temperature respectively) oil and NaOH alkaline solutions with different alkali concentrations at 22 and 60°C are shown in Fig. 2. The acidity of Safaniya crude oil was determined using the Institute of Petroleum procedures Nos. 1 and 182 [21]. The organic acidity was found to be about 1.4 mg KOH/g per sample of crude oil, which makes the crude oil a good example for recovery by alkaline flooding.

The contact angles that the oil droplet makes with a very smoothed rock surface in presence of alkaline solution were measured. The oil droplet was put in contact with the downward surface of rock sample. The droplet was photographed at periodic time intervals until equilibrium was reached. The contact angle measurements of Safaniya crude oil droplet with sandstone and limestone samples are given in Fig. 3. This provides a measure of rock wettability.

pH values of different alkaline solution concentration were measured by using the digital pH meter. pH values for different alkali (NaOH) solutions are shown in Fig. 4.

The viscosities of Safaniya crude oil (which is Newtonian fluid) were measured by a viscometer of a capillary type. Figure 5 is a plot of crude oil viscosity at different temperatures, in order to explain the behavior of mobility ratio in the displacement process.

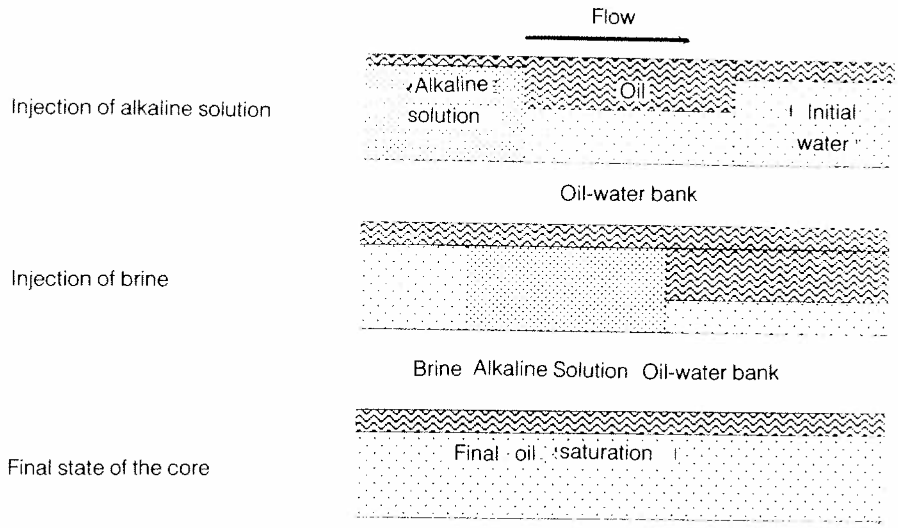

Fig. 1. Schematic diagram of the core saturation at different stages.

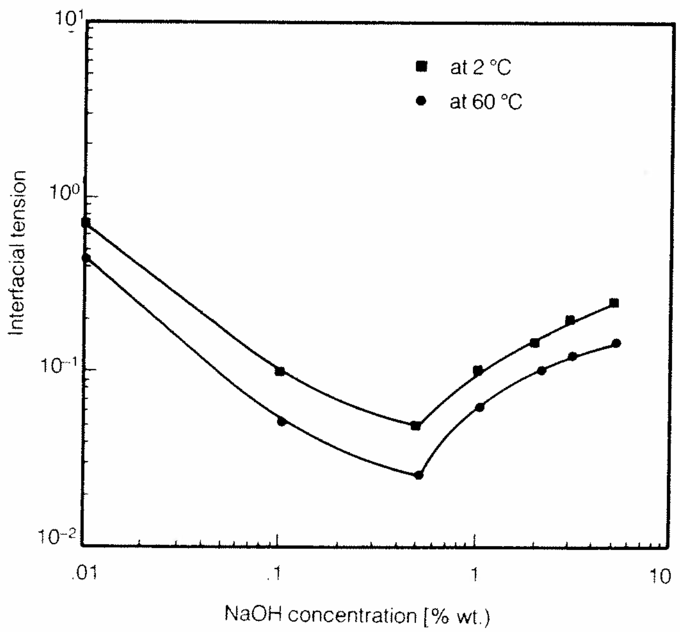

Fig. 2. Effect of alkaline concentration on interfacial between Salaniyah crude oil and NaOh solution.

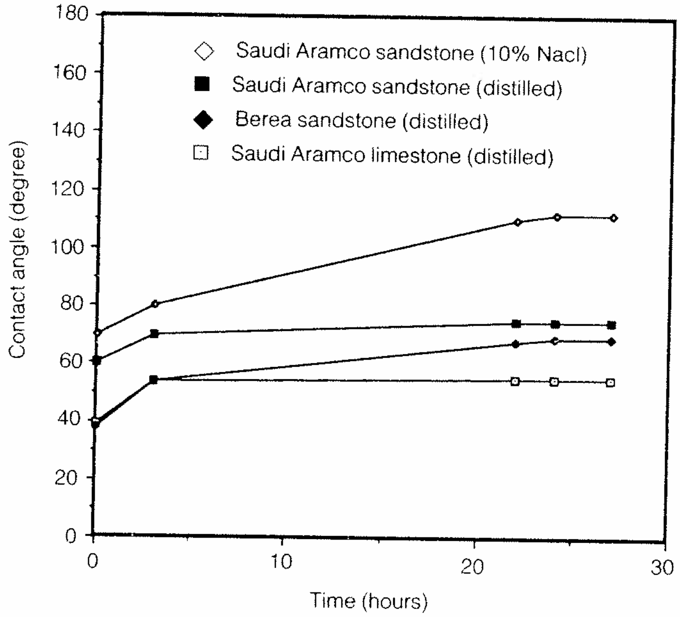

Fig. 3. Contact angle vs time for Safaniyah crude oil in water at 22°C. (Equilibrium time equal to about 24 hours).

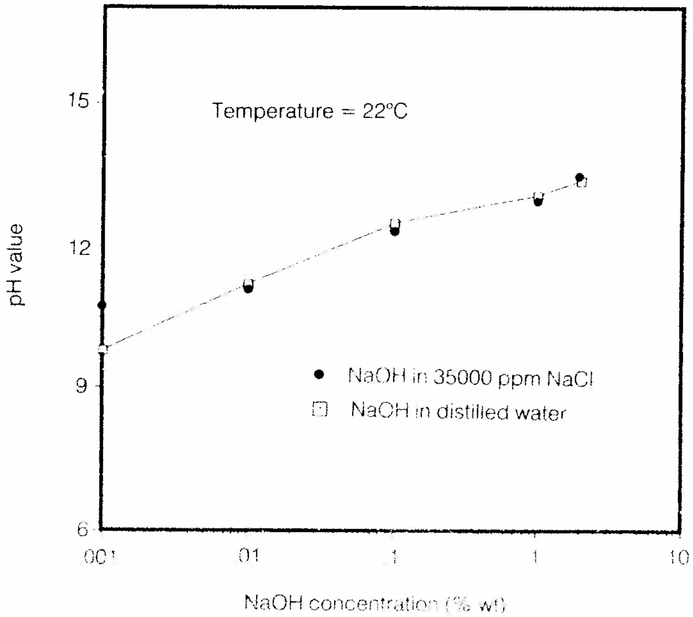

Fig. 4. pH value vs. naOH concentration.

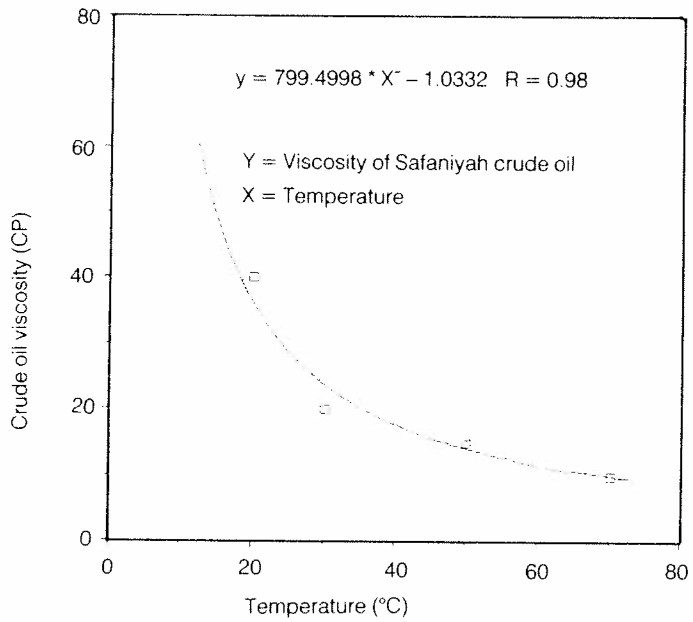

Fig. 5. Effect of temperature on Safaniyah crude oil viscosity.

Sandstone and limestone samples, having 3.80 cm inside diameter and 7.6 cm length, were (obtained from Saudi Aramco) used in displacement tests. Some other tests were carried out in Berea sandstone cores to investigate the effect of temperature on alkaline displacement process. The properties of these samples are shown in Table 1. The mineralogical analysis of the different cores are shown in Table 2. Non-clay minerals were identified with a petrographic microscope. The structure of the clays was determined by using a Zeiss EM109 electron microscope. Clay fractions were analyzed using HF dissolution and elemental determinations by atomic absorption using acetylene and nitrous oxide gases.

Apparatus

A schematic diagram of experimental apparatus used in the displacement experiments is shown in Fig. 6.

Oven assembly (Fig. 6a) provides temperature control during testing. It consists of a core holder, heater coils for both oil and water, heating elements for the air within the oven, an oil filter, a thermometer and an air circulating fan. The core holder is a vessel designed to hold the core sample under reservoir conditions of overburden pressure up to 10000 psig.

Table 1. Properties of core samples

Type	Porosity (%)	Absolute permeability (md)
Berea sandstone	13.15	363.8
Saudi Aramco sandstone	19.57	4.16
Saudi Aramco limestone	11.73	7.63

Table 2. Mineralogical analysis of sandstone and limestone cores [7]

	Mineralogical composition (% wt)				%Relative abundance of clay families			
Type	Quartz	Feldspars	Other minerals	Clays	Kaolinite	Chlorite	Illite	Montmo-rillonite
Saudi Aramco sandstone	85	3	4	5	40	27	17	6
Saudi Aracmo limestone	traces	--	--	6	98	--	traces	--
Berea sandstone	75	10	5	5	63	9	25	traces

The control panel is the control unit of system (Fig. 6b). It consists of overburden pressure, the confining pressure on the core sample, upstream pressure which pushes fluids into and through the core sample. A digital transducer which shows the pressure difference between upstream and downstream pressures, and two liter free piston accumulators and back pressure regulator multiplier are mounted behind the panel control.

Two-pressure multiplier accumulators supply brine (water) to the system (Fig. 6c). The output pressure from the accumulators is approximately 4.5 times the input pressure.

There are three rack accumulators. One is filled with reservoir crude oil, other is filled with alkaline, and the third is filled with mercury (Fig. 6c). Two tanks of nitrogen with regulators to maintain the piston in certain position within the accumulator. Hand pump applies pressure to the core holder by using water as a pressure medium.

The main purpose of the flow system is to conduct oil and water into the core samples. Fluid is driven from the pressure multiplier accumulators in-the mercury reservoir, the mercury pushes the oil (or alkaline) into the core sample, the oil (or alkaline) is heated in the oven's heater coils before entering the core holder. The oil is filtered before entry into the core sample.

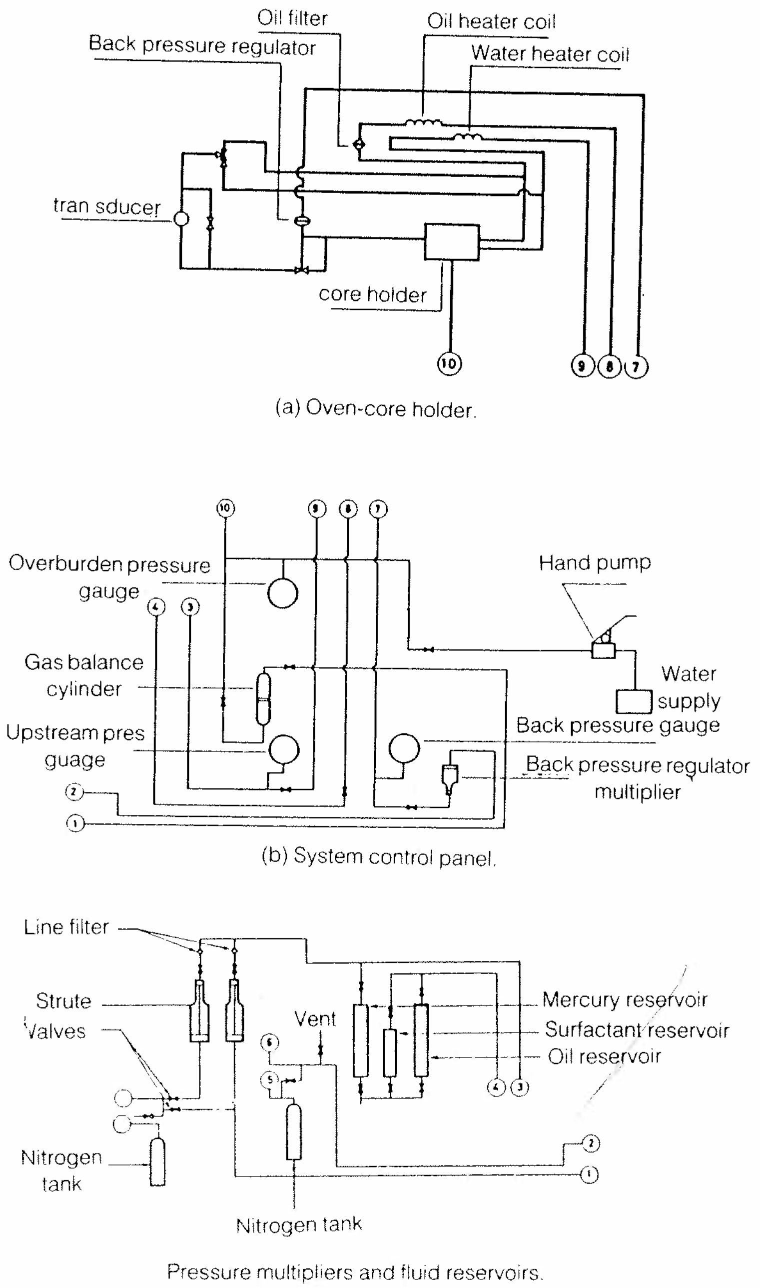

Fig. 6. Displacement apparatus for consolidated cores.

Preparation of the cores and procedure

The core samples were initially evacuated and saturated with formation water. (25%) sodium chloride brine), then flooded with Safaniya crude oil, and thereafter waterflooded with sea brine 3.5% sodium chloride brine). The core then attained the residual oil saturation and a tertiary NaOH alkaline flood could then be initiated. The same brine was used for driving the alkaline solution.

Experimental Results and Discussion

All displacement tests were performed under the same conditions of porosity and permeability. All chemical solutions were freshly prepared just before being used to avoid any effect of air exposure which may alter the surface tension. A summary of the displacement results is shown in Table 3.

Table 3. Summary of displacement tests

Run No.	Core type	Initial oil saturation	Pore volume	Oil recovery (% OIP)	Temperature (°C)	NaOH concentration (% wt)
1	Berea sandstone	0.846	5.7	81.6	60	0.5
2	Berea sandstone	0.883	5.0	68.0	22	0.5
3	Saudi Aramco sandstone	0.835	5.2	84.0	22	1.0
4	Berea sandstone	0.881	5.0	74.0	40	0.5
5	Saudi Aramco sandstone	0.887	3.7	73.7	22	0.5
6	Saudi Aramco limestone	0.808	5.2	87.0	22	0.5

Effect of alkaline (NaOH) concentration on cumulative oil recovery

The cumulative oil recovery and percent oil in samples produced from Saudi Aramco sandstone core by 0.5 and 1.0 weight percent of NaOH concentrations at temperature of 22°C is shown in Figs. 7 and 8. The effect of alkaline NaOH concentration on oil recovery is shown in Fig. 9.

It can be seen from these experiments that alkaline tertiary floods recovery more oil than conventional waterfloods. This increase in cumulative oil recovery is evidenced by the production of a large stabilized oil-water bank in the tertiary stage as shown in Figs. 7 and 8. It is shown from these figures that the duration of waterflooding is from 1.5 to 2 pore volumes to attain residual oil (S_{or}). About 0.25

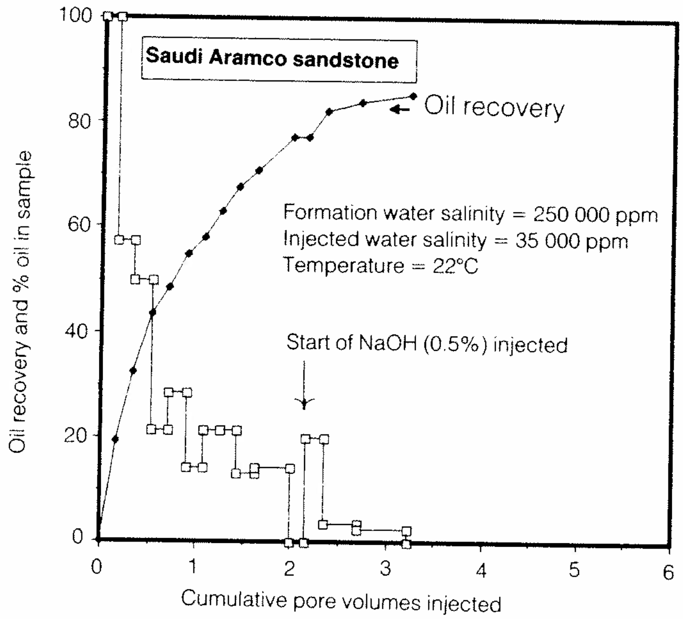

Fig. 7. Production history for Safaniyah crude oil displacement by tertiary alkaline water-flooding from sandstone core.

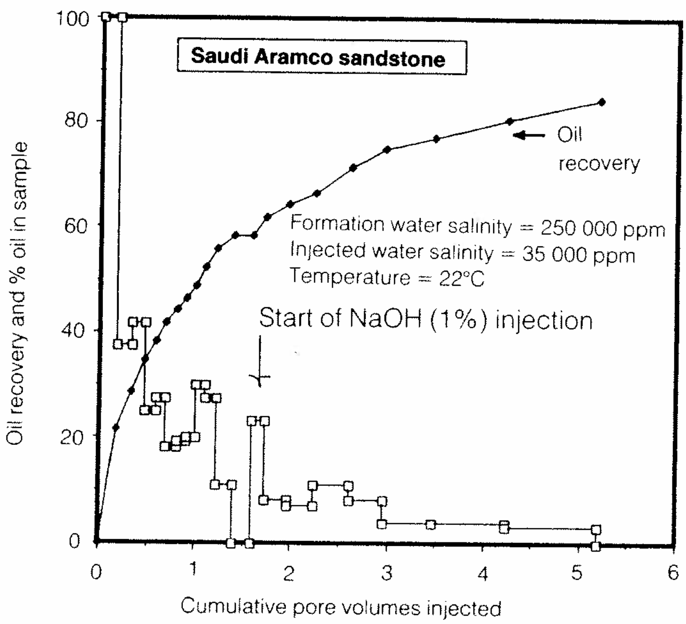

Fig. 8. Production history for Safaniyah crude oil displacement by tertiary alkaline water-flooding from sandstone core.

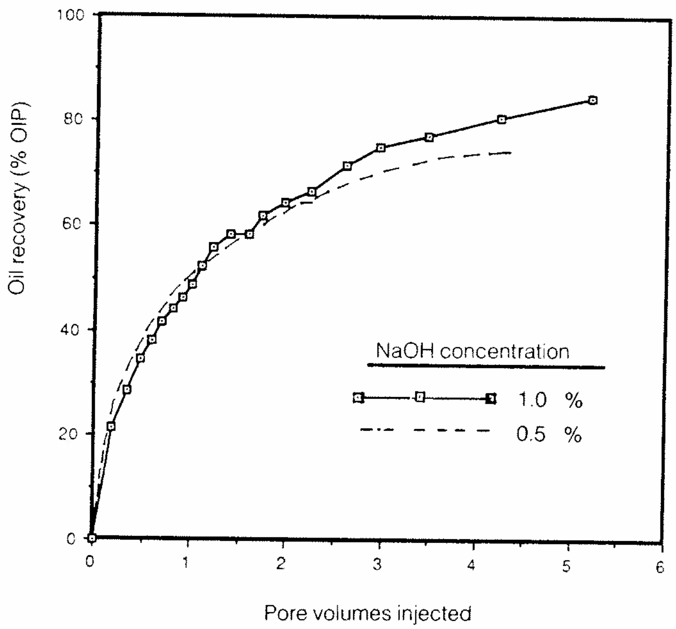

Fig. 9. Effect of NaOH concentration on oil recovery from Saudi Aramco sandstone core.

pore volume of water was produced before the breakthrough of the oil bank. Since Safaniya crude oil has a high acid number, the efect of alkali on oil recovery is due to chemical reactions between alkali and organic acids occurring in the crude oil. These reactions result in the formation of surface active material. These materials decrease the interfacial tension between oil and water.

Increasing the concentration of NaOH in the displacing water resulted in an increase in oil recovery (up to 10% oil in place) as shown in Fig. 9. This behavior can be explained by the effect of caustic concentration on both interfacial tension and pH value of the solution. As shown in Fig. 2, increasing NaOH concentration decreases the interfacial tension between Safaniya crude oil and alkaline water. The decrease reaches maximum in the range from 0.4 to 0.5 weight percent of NaOH concentration. Due to diffusion and adsorption of NaOH ions on grain surfaces, it is apparent that a much higher concentration is necessary in practical floods. It should be observed also that the miscibility between crude oil and caustic water occurs locally and may break shortly after it develops. The change in pH value as NaOH concentration increases shown in Fig. 4 indicates that pH value between 10-12 is obtained at NaOH concentration of 0.01 and 0.5. This range of pH value is considered optimum for oil recovery [20].

Effect of rock mineralogical composition on oil recovery

In order to investigate the effect of the rock composition on the displacement efficiency by alkaline flooding, three tests were carried out on Saudi sandstone, Saudi limestone and Berea sandstone.

Figures 7, 10 and 11 represent the production history for Safaniya crude oil displacements by tertiary alkaline water from Aramco sandstone, Aramco limestone and Berea sandstone cores. It is clear from Fig. 12 that the highest oil recovery was obtained when Saudi Aramco limestone was used. This behavior can be explained by the effect of rock composition on wettability. As shown in Fig. 5, the lowest contact angle obtained was on a limestone surface.

Examination of the cores with the scanning electron microscope showed that Aramco sandstone consists of sand sized grains cemented by partial grain coatings of clays. Kaolinite affects rock petrophysical properties. The examination of Saudi sandstone after flow tests showed that the clay coating on the sand grains had migrated into pore throats. This resulted in lower oil recovery. The percentage of clays in Aramco carbonate cores was too low to be detected by the scanning microscope [22]. This, we believe, resulted in higher recovery. This behavior is supported by the effect of contact angle explained above.

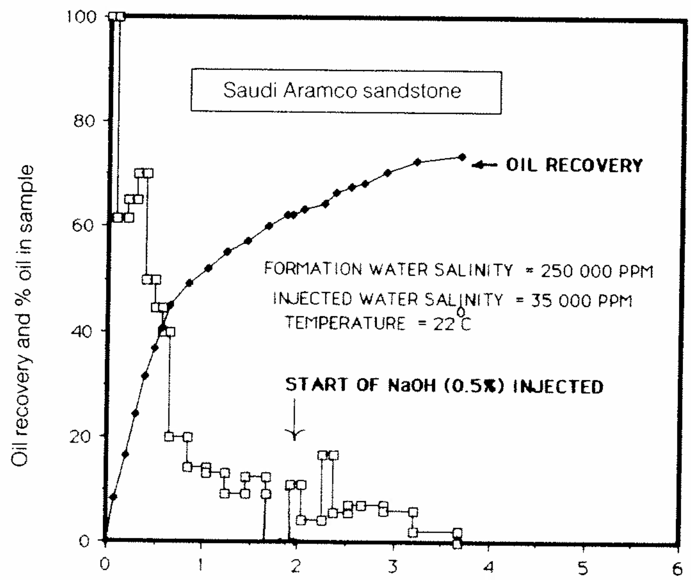

Fig. 10. Production history for Safaniyah crude oil displacement by tertiary alkaline water-flooding from limestone core.

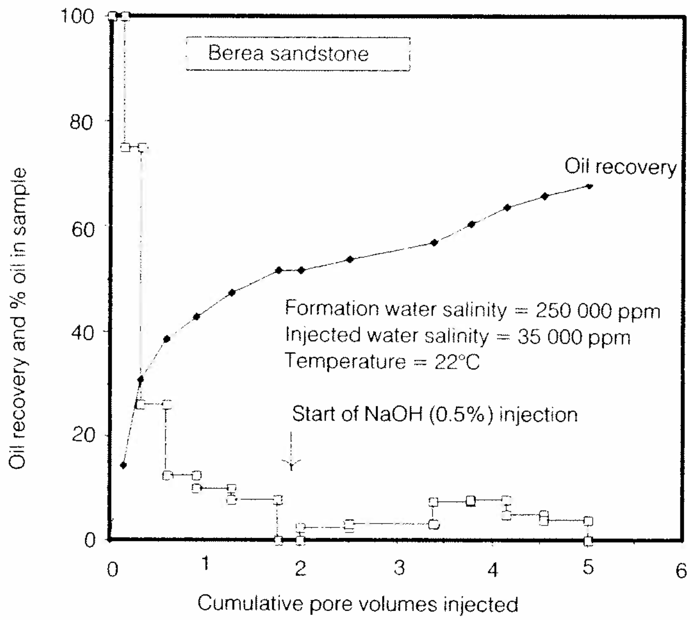

Fig. 11. Production history for Safaniyah crude oil displacement by tertiary alkaline water-flooding from Berea sandstone cores at 22°C.

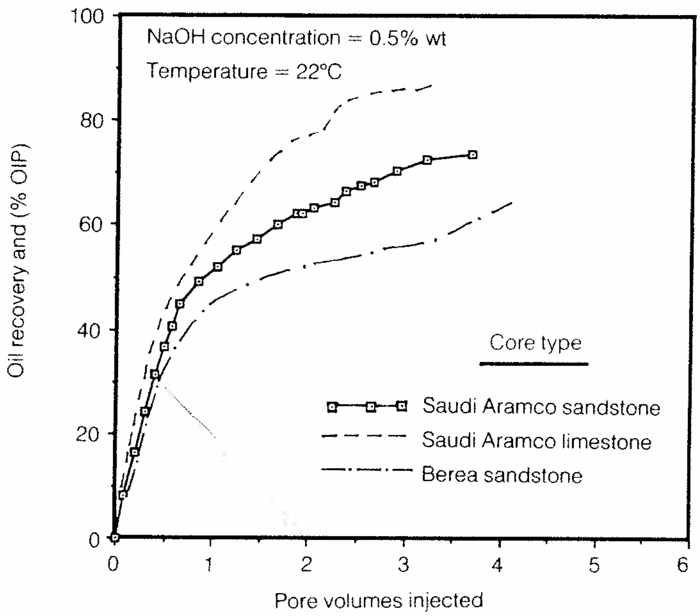

Fig. 12. Oil recovery vs. pore volumes injected for Berea Sandstone, Saudi Aramco (sandstone and Saudi Aramco limestone.

Effect of temperature on alkaline flooding

Temperature plays an important role in alkaline flooding. It affects the interfacial tensions as shown in Fig. 2 and wettability properties [23]. It also affects the viscosity of the crude oil, as shown in Fig. 5, leading to remarkable changes in the mobility control of the process and hence in oil recovery. Hence, Berea sandstone cores (which are available) were used in order to investigate the effects of temperature on the process behavior.

Figures 11, 13, and 14 show the production histories of three tertiary alkaline floods using 0.5 weiht percent NaOH at 22°C, 40°C and 60°C, respectively. The effect of temperature on oil recovery is shown in Fig. 15.

It can be seen from Fig. 15 that an increase in oil recovery was obtained with an increase in temperature. From Fig. 2, which shows the interfacial tension between Safaniya crude oil and alkaline NaOH solutions at 22°C and 60°C, it can be seen that interfacial tension decreases with increasing temperature. Figure 5 shows that Safaniya crude oil viscosity decreases with increasing temperature.

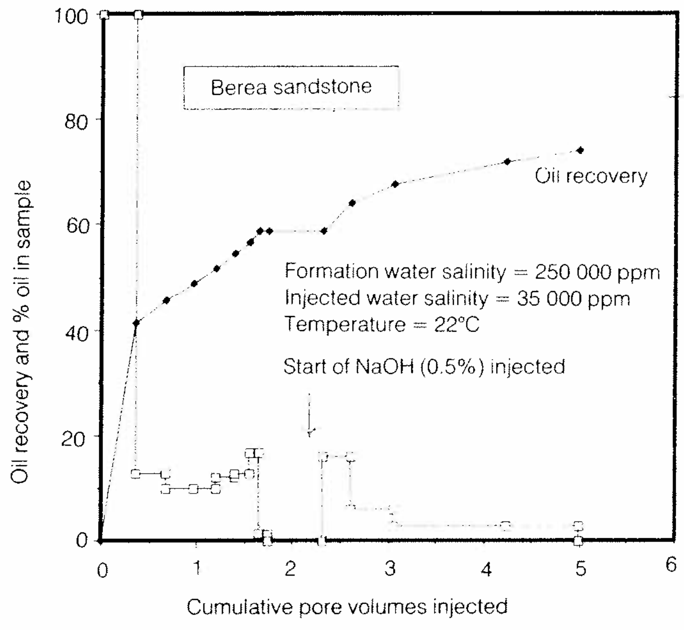

Fig. 13. Production history for Safaniyah crude oil displacement by tertiary alkaline water-flooding from Berea sandstone core at 40°C.

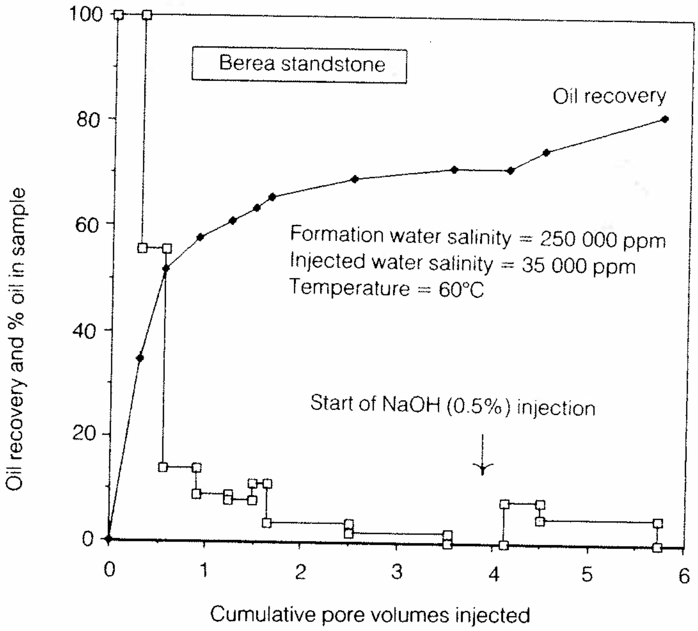

Fig. 14. Production history for Safaniyah crude oil displacement by tertiary alkaline water-flooding from Berea sandstone core at 60°C.

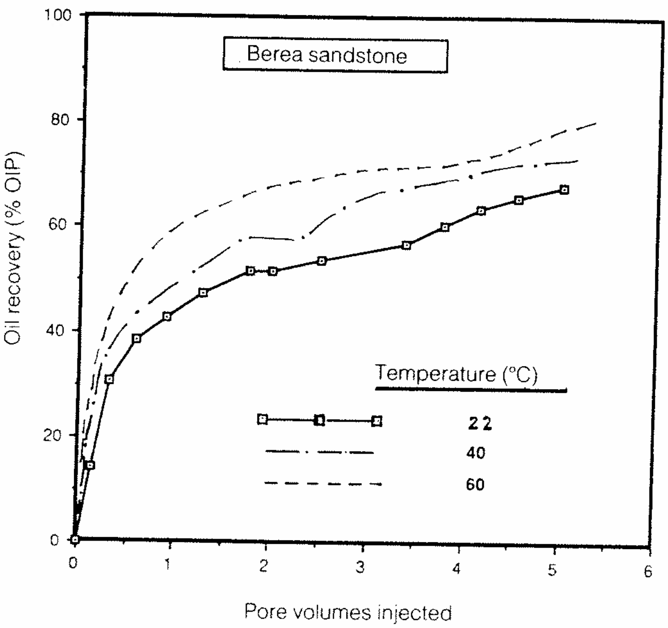

Fig. 15. Effect of temperature on tertiary alkaline flooding.

Therefore, it can be said that the increase in oil recovery at the higher temperature is a result of the lower interfacial tension and the better mobility ratio between oil and displacement water due to decreasing oil viscosity. Temperature affects, to greater extent, the viscosity of the fluids in porous medium, leading to remarkable changes in mobility control of the process and hence in oil recovery.

Process Economics

An approach for economic evaluation of crude oil displacement by chemical solutions was introduced by the authors previously [24]. The approach developed was based on a probability distribution of escalating prices of oil, chemicals and brine operating and capital costs. Many mathematical modesl have been formulated for the economical evaluation of enhanced oil recovery projects [25-31].

In a fluid injection operation the amount of economic recovery is controlled by a combination of factors which are quantitatively different from one reservoir to another. Some factors are natural derived, others are controllable. One of the most important of these factors is the displacement efficiency or recovery factor. Economic factors scan overshadow physical factors in economical oil production. The economical feasibility of alkaline flooding that can be applied under Safaniya reservoir conditions must be carried out [32]. Therefore, this part of study is an effort to apply economic considerations to alkaline waterflood with the aim of estimating roughly the costs of recoverable oil by NaOH solutions of different alkaline concentrations.

Typical types of cost required for an alkaline waterflood project

a) Start-up costs which includes both the cost of equipments to mix and inject slug and to soften water and costs of converting of some of the producing wells to injection wells (C_{su}).

b) Operating include (i) fixed operating costs which are assumed to be the same as the operating expenses for waterflood (C_{pf}), and (ii) variable operating costs which are mainly for the preparation and injection of NaOH solution, water disposal and produced oil treatment (C_{pv}).

c) NaOH agent costs (C_{ch}).

d) Some other operating costs such as labor and equipment rental, electricity, services and project plan and design services (C_{oth}).

The NaOH costs can be determined by using the following equations:

$$C_{ch} = (3.498) \frac{[P_{NaOH}][V_s][\rho][C]}{[R_o][S_{oi}]} (\$/bbl) \quad (1)$$

where, P_{NaOH} = prices of NaOH alkaline, \$/lb)
V_s = slug size, % pore volume
ρ = solution density, gm/cc
C = NaOH concentration, weight %
R_o = cumulative oil recovery, % OIP
S_{oi} = initial oil saturation, fraction

The values of these parameters are listed in Tables 3 through 6. Table 4 shows the estimated alkaline chemical costs for different nominal crude oil prices. The estimated operating costs for chemical flooding processes are presented in Table 5. An estimate of the other costs is presented in Table 6. The calculations are based on NaOH prices presented in tables 4 and 5 and 1 gm/cc for solution density. The net cash flow per barrel of the oil recovered by alkaline waterflood is dependent on both the nominal crude oil prices and the total costs per barrel to be recovered, i.e.

Table 4. Price estimate for chemicals used chemical flooding at various nominal oil prices [24]

Chemical cost (\$ / Active pound)				
Chemical	**\$20/bbl**	**\$30/bbl**	**\$40/bbl**	**\$50/bbl**
Primary surfactants	0.27	0.32	0.37	0.42
Secondary surfactants	0.37	0.44	0.51	0.58
Polymers	1.42	1.60	1.78	1.96
Alkaline agents	0.15	0.17	0.19	0.21

Table 5. Variable operating expenses for chemical flooding (Dollars/bbl) [24]

	Surfactant	Polymer	Alkaline
Chemical slug injection	0.20	–	0.1
Polymer solution injection	0.10	0.10	0.10
Produced water disposal	0.03	0.03	0.03
Produced oil treatment	0.50	0.05	0.50

Table 6. Other project costs ($/bbl) [24]

Start up costs	3.00
Labor and equipment rental	1.76
Electricity and service facility	1.86
Laboratory services and re-drilling wells	5.6

$$\text{Net Cash flow} = [\text{crude oil price}] - [\text{flood costs}]$$

or

$$\text{New cash flow} = [\text{crude oil price}] - [C_{su} + C_{pf} + C_{pv} + C_{ch} + C_{other}] \quad (2)$$

Based on the data shown in Tables 4 through 6, Equation 2 can be written as:

$$\text{Net cash flow} = [\text{crude oil price}] - [C_{ch} + 12.35] \quad (3)$$

The results of net cash flow per barrel calculations on the basis of Equation (3) for different crude oil prices are shown in Fig. 16. It is clear that the process is feasible under present oil prices of 20 dollars per barrel.

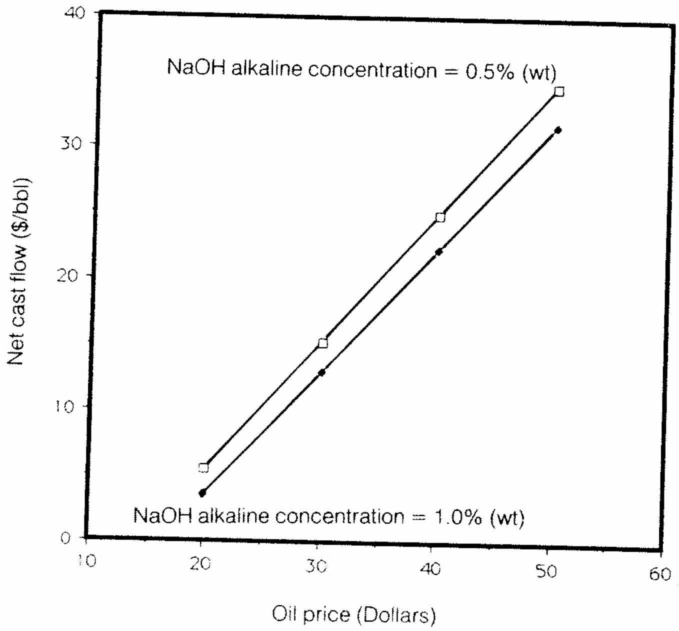

Fig. 16. Oil price Vs net cash flow for alkaline flooding.

Conclusions

For Safaniya crude oil and Saudi sandstone and limestone cores used and based on the results of this study, the following conclusions may be derived:

1) Tertiary alkaline NaOH waterfloods in Saudi sandstone and limestone recover more oil than does the conventional waterflood; because of the improvement in mobility and the decrease in oil/water interfacial tension. This increase in cumulative oil recovery is evidenced by production of a tertiary large stabilized oil-water bank.

2) Increasing NaOH concentration in the flood water increases oil recovery.

3) At applied conditions of 250,000 ppm salinity and 22°C temperature, more oil recovery by alkaline flooding was obtained when using limestone cores than with sandstone cores, due to the effect of rock composition on wettability.

4) Oil recovery increases with increasing temperature from 22°C to 60°C.

5) Tertiary alkaline waterflooding is expected to be effective under Safaniya reservoir conditions of salinity and temperature.

6) The alkaline waterflooding under Safaniya field conditons may be economically attractive.

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References

[1] Atkinson, H. "Recovery of Petroleum from Oil Bearing Sands." *U.S. Patent No.* 1, 651,311 (Nov. 29, 1927).

[2] Squires, F. "Method of Recovering Oil and Gas." *U.S. Patent No.* 1, 238,355 (1929).

[3] Nutting, P.G. "Chemical Problems in the Water Driving Petroleum from Oil Sands." *Ind. and Eng. Chem.* 17, (1927), 1035-1036.

[4] Nutting, P.G. "Principles Underlying Soda Process." *Oil and Gas J.* 25, No. 50 (1927), 32-34.

[5] Nuttings, P.G. "Petroleum Recovery by Soda Process." *Oil and Gas J.*, 27, No. 22 (1928), 146;238.

[6] Nutting, P.G. "Soda Process for Petroleum Recovery." *Oil and Gas J.* 25, No. 45 (1927).

[7] Sayyouh, M.H. and Al-Blehed, M.S. "Areal Sweep Efficiency in Polymer, Alkaline and Micellar Flooding of Saudi Crude Oil." *Final Report No. PE-2/412, Research Center, the College of Engineering,* KSU (1992).

[8] Johnson, C.E. "Status of Caustic and Emulsion Methods." *JPT* (Jan. 1976), 85-92.

[9] Jennings, H.Y. Jr.; Johnson, C.E., Jr. and McAuliffe, C.D. "A Caustic Waterflooding Process for Heavy Oils." *J. Pet. Tech.* (Dec. 1974), 1344-1352.

[10] Ehrlich, R. and Wygal, R., Jr. "Interrelation of Crude OIl and Rock Properties with the Recovery of Oil by Caustic Waterflooding." *SPEJ* (August, 1977), 263-270.

[11] Jennings, H.Y. Jr. "A Study of Caustic Solution Crude Oil Interfacial Tensions." *Soc. Pet. Eng.* 15, No. 31 (1975), 197-202.

[12] Novosad, Z.S. *et al.* "Comparison of OIl Recovery Potential of Sodium Orthosilicates and Sodium Hydroxide for the Wainrgiht Reservoir, Albert." *Petroleum Recovery Inst., Report No. 18-10,* Alta, Canada (July 1981).

[13] Burke, J.H. "Comparison of Sodium Carbonate, Sodium Hydroxide, and Sodium Orthsilicate for EOR." *SPE Reservoir Engineering* (Feb. 1987), 9-16.

[14] Cooke, C.E., Jr.; Williams, R.E. and Kolodzie, P.A. "Oil Recovery by Alkaline Waterflodding." *JPT* (Dec. 1974), 1365-1379.

[15] Dokla, M.E.; Sayyouh, M.H. and Totonji, A. "Application of Caustic Waterflooding to Saudi Reservoirs." U.S.A., *J.M.S.E.*, Vol. II, No. 4 (1982), 2192-2195.

[16] Sayyouh, M.H. *Improved Oil Recovery Methods.* Cairo University: Energy Research Center, March 1986.

[17] Al-Sughayer, A.A. "Effect of Clay Content on Enhanced Oil Recovery by Polymer and Alkaline Flooding in High Salinity Reservoirs." *M.Sc. Thesis,* KSU (1989).

[18] Raimondi, P.R.; Gallagher, B.J.; Eurlich, R.; Messmer, J.H. and Bennett, G.S. "Alkaline Water Flooding: Design and Implementation of a Field Pilot." *JPT* (Oct. 1977), 1359-1368.

[19] Sayyouh, M.H.; Abdel Waly, A.; Awara, A. and Osman, A. "Application of Alkaline Waterflooding to a High Acidity Crude Oil." France, *Revue de L'Institut Francais du Petrole,* 44, No. 4 (July 1989), 461-476.

[20] Dokla, M.E. "Effect of Formation Heterogeneity and Temperature on Alkaline Waterflooding Performance." paper SPE 9649, *Proceedings, Middle East Oil Technical Conference,* (March 1981), 669-676.

[21] Institute of Petroleum. *IP Standards for Petroleum and Its Products, Part-1: Methods for Analysis and Testing.* London: The Institute of Petroleum, 1980.

[22] Dahab, A.; Omar, A. and Sayyouh, M.H. "Role of Clays in Influencing Permeability Damage, Capillary Pressure at Wettability Characteristics." *Journal of JPI,* 36, No. 3 (1993), 197-203.

[23] Sayyouh, M.H. and Al-Blehed, M.S. "Effects of Some Middle East Crude Oils-Brine-Rock Interactions on Wettability." Japan: *J.P.I.*, 34, (1991), 284-290.

[24] Al-Blehed, M.S.; Sayyouh, M.H. and Desouky, S.M. "An Engineering-economic Evaluations of Enhanced Oil Recovery of Saudi Crudes by Chemical Flooding." *Journal of Engineering Costs and Production Economics, Elsevier,* 21, (1991), 105-109.

[25] Gittler, W. and Krumrine, P. "A Novel Approach for Risk Assessment in Chemical EOR Projects." paper SPE 13767, presented at the SPE 1985 *Hydrocarbon Economics and Evaluation Symposium,* (March 14-15, 1985), 67-79.

[26] Stanley, C.J. "Finding the Most Profitable Slug Size." *J. Pet. Technol.* (August 1972), 993-994.

[27] Ramey, H. and Brigham, W. "Heavy Oil REcovery Research Program at SUPRI." *Proc. SPE/DOE Enhanced Oil Recovery Symp.*, Tulsa (1979), 61-65.

[28] Matheny, S.L. "EOR Methods Help Ultimate Recovery." *Oil and Gas J.* (March 31, 1980), 38; 47.

[29] Richard, L.W.; Brown, S.L. and Ramy, H.J. "Economic Appraisal of Thermal Drive Projects - A New Approach." *55th Annual Fall Technical Conference and Exhibition,* SPE/AIME, Dallas, Texas. (Sept. 21-24, 1980), 1-6.

[30] Ramirez, W.F.; Fathi, Z. and Cagnol, J.L. "Optimal Injection Policies for Enhanced Oil Recovery: Part 1 - Theory and Computational Strategies." *SPE J.* (June 1984), 84-96.

[31] Sayyouh, M.H. and Al-Blehed, M.S. "Screening Criteria for Enhanced Recovery of Saudi Crude Oils." *Energy Sources,* 12, (1990), 71-82.