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Screening Criteria for Enhanced Recovery of Saudi Crude Oils

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Abstract *The principal objective of this investigation was to study and analyze the screening guides that can be used to select the applicable enhanced oil recovery (EOR) method under Saudi oil field conditions. Based on the analysis of data obtained from 186 Saudi formations, the crude oils are produced from low to intermediate permeability formations in the range of 1–1500 millidarcies. The original reservoirs' pressure and temperature range from 2000 to 5500 psi and from 140 to 240°F, respectively. The porosity of the formations varies form 10 to 30% and the formations thickness ranges from 10 to 300 feet. The reservoirs of Saudi Arabia are characterized by high formation water salinity, which can be as high as 30% by weight. Saudi oil formations are characterized by connate water in the range of 10–50%. Thus residual oil saturation is expected to be high. The viscosity of most Saudi crude oils ranges from 0.10 to 10 centipoise. The API gravity ranges from 15 to 45.*

The basic parameters studied include formation permeability, porosity, and thickness; reservoir pressure and temperature; crude oil viscosity and API gravity, formation connate water saturation and its salinity, and formation type and heterogeneity.

Based on the screening analysis discussed in this article, it was found that the most suitable technical methods applicable to Saudi oil fields are the miscible processes using gases. A new technology should be developed in order to be able to apply any of the enhanced recovery methods involving chemicals. This will require extensive laboratory work. In addition, in order to select the most efficient enhanced oil recovery (EOR) process, it is necessary to simulate reservoir conditions in laboratory studies.

Keywords: Screening criteria, enhanced oil recovery, Saudi fields, chemical flooding, miscible flooding, steam flooding, fire flood.

Introduction

According to the latest published data, the original oil in place in Saudi Arabia is about 700 billion barrels. Only about 250 billion barrels, or 35% of total oil in place, can be produced by conventional production methods. More than 90 billion barrels, as much as twice the proven reserve of the U.S. and Canada combined, can be added to the country's proven reserve if only 20% out of the 450 billion barrels left in place can be produced through enhanced oil recovery methods.

By definition, enhanced oil recovery (EOR) means the additional recovery of liquid hydrocarbon from known oil or tar and reservoirs not technically or economically feasible by conventional methods (Perry 1981). Thus, the oil remaining after conventional methods have been employed is the target of enhanced oil recovery methods. These methods may be divided into two main categories: thermal and nonthermal displacement processes (Sayyouh 1986). The nonthermal methods include: polymer flooding, micellar flooding, alkaline waterflooding, and miscible displacement process.

The use of polymer solutions in enhanced oil recovery operations is now commonplace. There are three basic types of polymers that are used in EOR operations: polyacrylamides, polysaccharides, and polyethylene oxides. The addition of a polymer to water helps to control water mobility. This results from increasing water viscosity and hence reducing its mobility. Interaction between the flowing polymer solution and formation reduces formation permeability through polymer retention. This constitutes another source of resistance to water flow. The net result is an improvement in the mobility ratio, and hence an increase in oil recovery, which is of the order of 5%.

Displacement by micellar solutions (known by various names) is one of the important nonthermal recovery processes. A micellar solution is a thermodynamically stable emulsion of oil and water in which the particle size of the emulsified or internal phase is less than 0.1 micron. Micellar flooding involves sequential injection of a micellar solution slug, a polymer solution slug for mobility control, and brine to drive these solutions. The process is strongly dependent on the properties of the rock and fluid characteristics, and must be tailored for a given reservoir.

An understanding of the mechanisms by which micellar solutions mobilize residual oil under tertiary conditions is needed for rational design for field conditions. In addition to economic considerations related to the cost of the surfactant and polymer additives, the high salinity condition for some fields place restrictions on the use of micellar-type flood.

In alkaline waterflooding, reaction between the alkaline solution and certain organic acids present in crude oils results in the formation of surfactants, which enhance emulsification, as a result of reduction in the interfacial tension.

The rock wettability may be altered by the reaction of alkaline solution with reservoir rock. This wettability change results in increase of oil recovery, because the water wetness of the rock increases.

There is increasing interest in the field applications of carbon dioxide flooding. When carbon dioxide (gas) is injected into a reservoir, it dissolves with crude oil at reservoir conditions and reduces its viscosity and causes it to swell. In miscible carbon dioxide flooding, liquid CO_2 mixes with oil, and through a mechanism of multicontact phase equilibrium, eventually achieves miscibility. This will increase recovery efficiency.

The miscible displacement process consists of displacing oil by injecting a solvent slug which is completely soluble in oil. The solvent slug is either liquid hydrocarbon such as naphtha and alcohol or liquified petroleum gas (LPG) such as butane and propane. There are three types of miscible displacement processes: (1) miscible slug process, in which a slug of liquid hydrocarbon is driven by gas, natural gas or water; (2) enriched gas process, in which an enriched gas slug is driven by lean gas or lean gas and water; and (3) high pressure gas process, in which a lean gas is injected under high pressure. This process is applicable to reservoirs containing highly volatile oil, and is sometimes called "vaporizing gas drive."

The term *thermal* EOR is used when heat is applied to the reservoir rock and fluid is driven by either steam, hot water injection, or in situ combustion. In the first case, heat is externally generated at the surface and injected into the formation, whereas in the case of in situ combustion heat is generated within the formation. The steam injection process takes two forms: (1) steam flooding involving continuous injection; and (2) cyclic steam stimulation, involving intermittent steam injection and oil production. In situ combustion can also take two forms: forward combustion (either dry or wet) and reverse combustion. The latter is seldom used. In the forward combustion process ignition is caused to occur at the injection well in the direction of air injection, whereas in reverse combustion the burning zone moves in a direction opposite to that of air. The increase in oil recovery, due to the application of heat to the reservoir rocks, is obtained mainly through reduction in oil viscosity and hence increase in sweep efficiency.

The screening guides for enhanced oil recovery methods should be used as a first step in evaluating a given oil reservoir for enhanced recovery. Many screening guides have been suggested for the application of EOR methods, according to field and laboratory results (El-Batanony et al. 1987; Taber 1983; Sawabini 1983; Schumacher 1980; Pelline 1982; Slider 1983; Geffen 1983; Poettmann 1974). The use of preferred criteria can be helpful in selecting suitable methods that may be economically attractive (Taber 1983). The main objective of this study was to investigate the screening guides of EOR methods that can be applied to Saudi oil fields.

Reservoir Parameters and Proposed Screening Approaches

In applying any EOR method to a given reservoir, it is important to evaluate properly the different reservoir parameters. Oil viscosity, API gravity, reservoir pressure and temperature, formation thickness, porosity, permeability, connate water saturation and salinity, rock clay sensitivity and heterogeneity are the more important factors that influence and

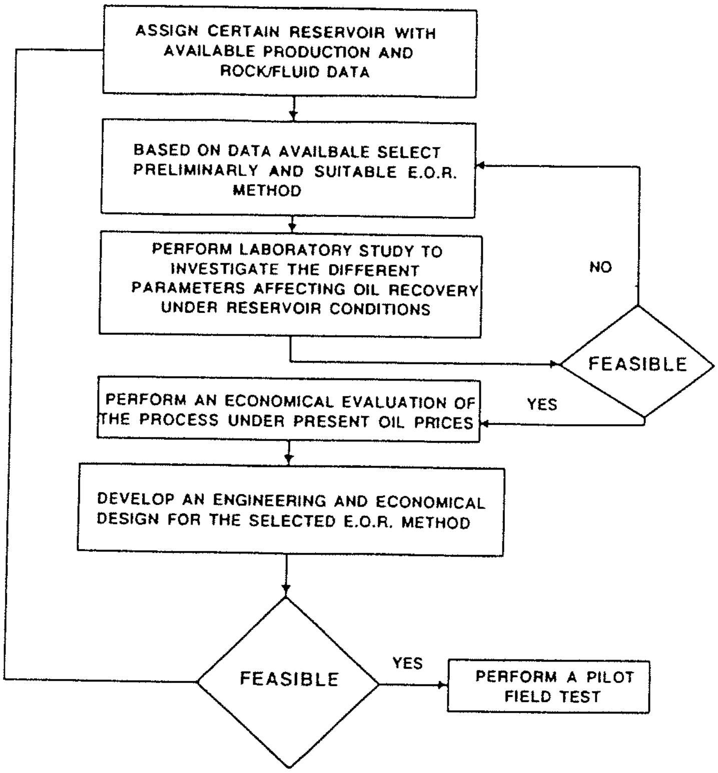

Figure 1. E.O.R. methods evaluation by using an individual reservoir approach.

limit the applicability of EOR processes. Another very important factor is reservoir geology. Geological conditions such as bottom water, shale barriers, gas caps, etc., can invalidate a favorable screening criterion. In the following, only the aforesaid parameters are considered for the Saudi reservoirs.

Two approaches are proposed as shown in Figures 1 and 2. The first approach shown in Figure 1 states that the reservoir should be evaluated individually, whereas the second approach presented in Figure 2 indicates that the screening guides should be used to select the best enhanced oil recovery method for a given reservoir.

Screening Guides and Saudi Oil Field Data Analysis

Figure 3 shows the different oil fields in the Kingdom of Saudi Arabia from which data was obtained and used in this study. The depth of major Saudi Arabian oil reservoirs is shown in Figure 4. A linear relationship between log Saudi crude oil viscosity and API gravity is presented in Figure 5.

Chemical Flooding

Enhanced oil recovery by chemical solutions is best applied to reservoirs with medium gravity crude oils as shown in Figure 6. Figure 7 shows that polymer, micellar, and alkaline flooding processes are applicable to reservoirs that contain crude oil viscosities up to 10 cp.

Most chemical enhanced oil recovery methods are applicable, preferably, to sandstone reservoirs. Reservoirs having extensive fractures and/or extreme reservoir heterogeneity are not practical candidates because of the resulting early breakthrough of the injected chemical slug. This is also true for the other EOR methods. The reservoir tempera-

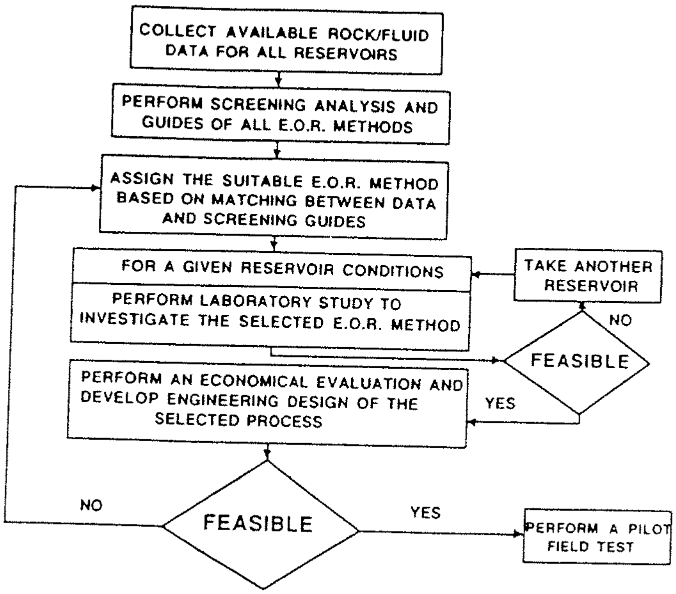

Figure 2. E.O.R. methods evaluation using screening analysis approach.

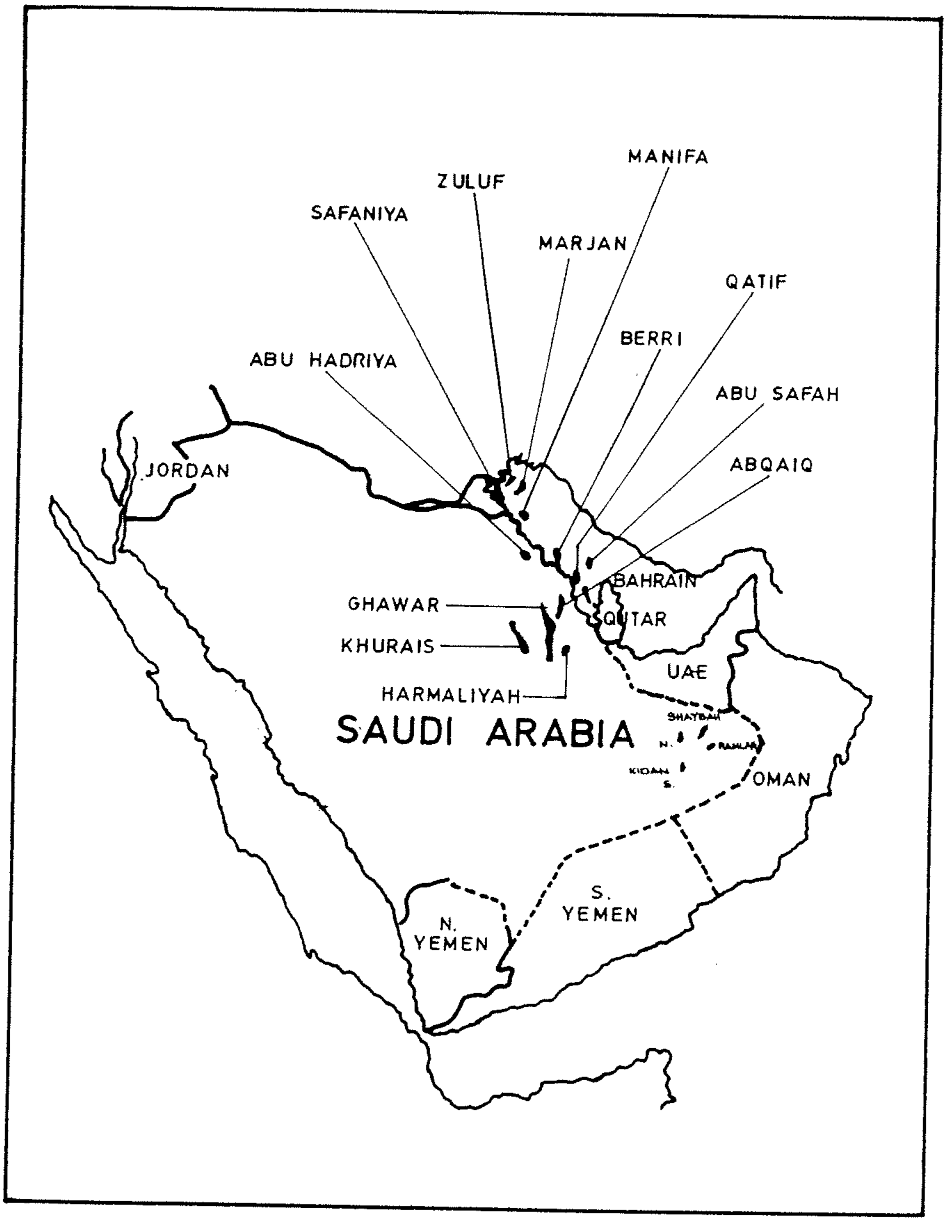

Figure 3. Kingdom of Saudi Arabia oil fields.

ture should not exceed 250°F as shown in Figure 8. However, extensive research is going on today in order to develop chemicals such as surfactants and polymers that can be used in reservoirs where the temperature is above this level. Fortunately, Figures 8 and 9 also indicate that Saudi reservoir temperature and pressure ranges from 140 to 240°F and from 2000 to 5500 psia, respectively, which means that the chemical methods are applicable at these ranges.

The reservoirs of Saudi Arabia are characterized by high salinity of the formation

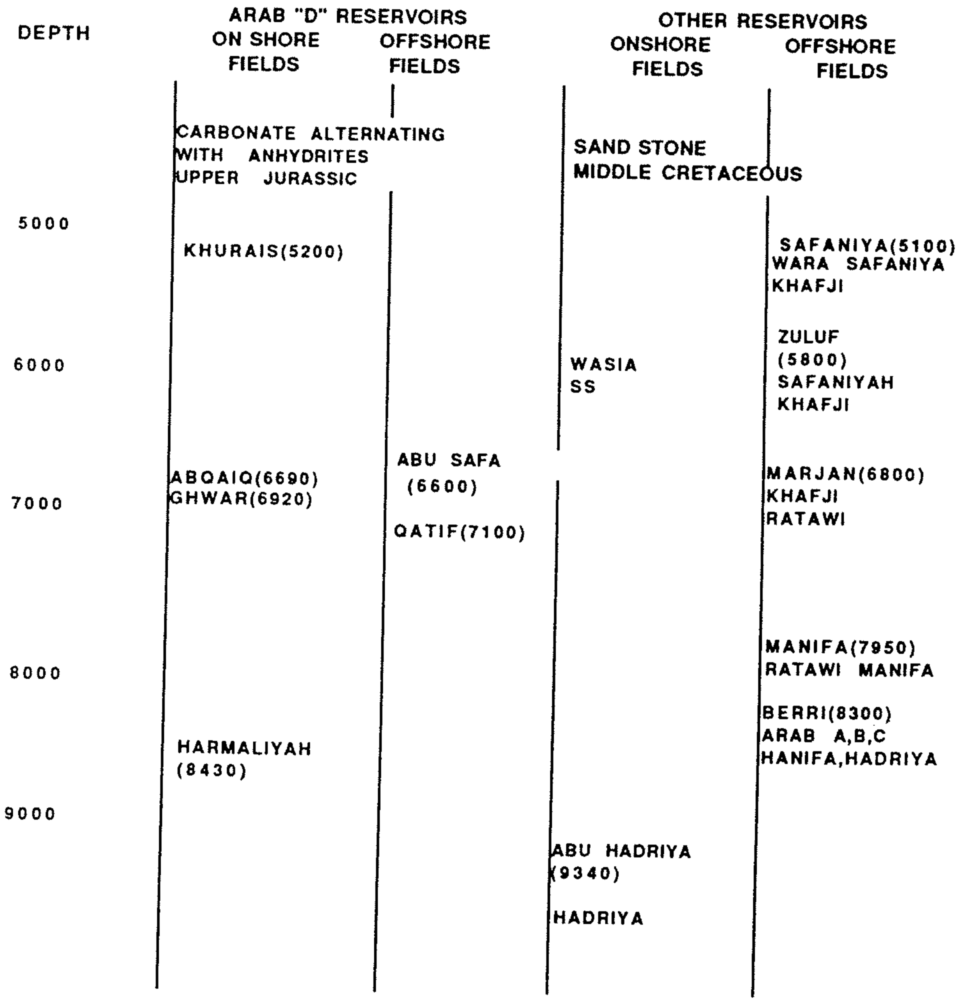

Figure 4. Major Saudi Arabian oil reservoirs.

waters as shown in Figure 10. This will put a serious limitation on the use of micellar and polymer floods. The high salinity of the formation water may reduce the integrity of the chemical slug. Therefore, for applying chemical methods to Saudi oil reservoirs, the chemicals should be chosen such that the adverse salinity effects can be minimized. In all cases, each reservoir must be evaluated individually.

Miscible Displacement

Figure 7 shows that enhanced oil recovery by CO_2 and miscible methods are feasible under Saudi reservoir conditions. Figures 11–14 show the feasibility of Saudi formations permeability, porosity, initial water saturation, and thickness, respectively, for applying different EOR methods. Figure 9 also shows the feasibility of Saudi original reservoir pressure for carbon dioxide flooding. The serious limitation on the use of CO_2 is its availability. Although it is expected that considerable amounts of CO_2 are generated from

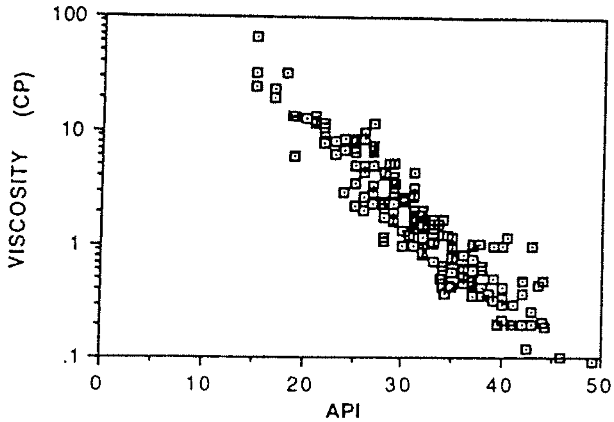

Figure 5. Saudi Crude oil viscosity vs. API gravity.

power plants and refineries, its storage and transportation will be economically questionable.

Thermal Flooding

Figure 7 also shows that the range of Saudi crude oil viscosities limits the use of some of the thermal methods. However, thermal recovery is being considered for higher gravity crudes than had been considered feasible in the past. Steam flooding has been very successful in light oils of over 20 field tests (Farouq Ali and Meldan 1979). In situ combustion has been more successful in lighter oils than in very heavy oils. Figure 6 shows that some of the thermal methods may be applicable to some of the Saudi oil reservoirs.

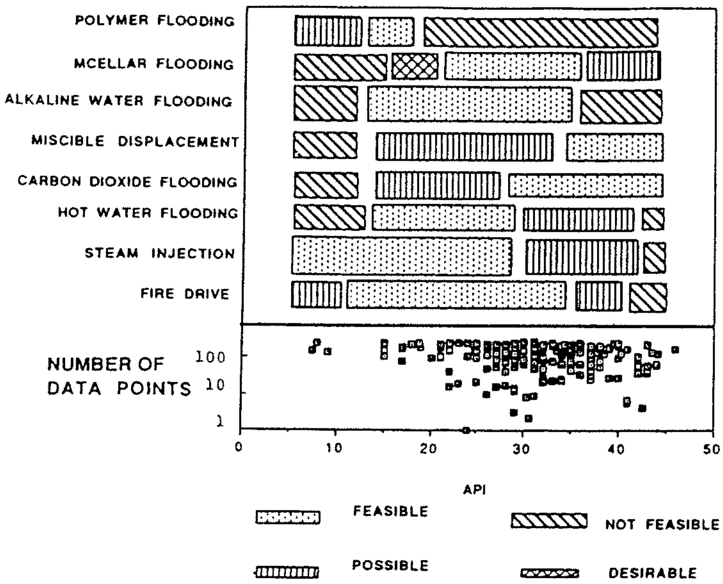

Figure 6. Saudi crude oil API gravity ranges for E.O.R. methods.

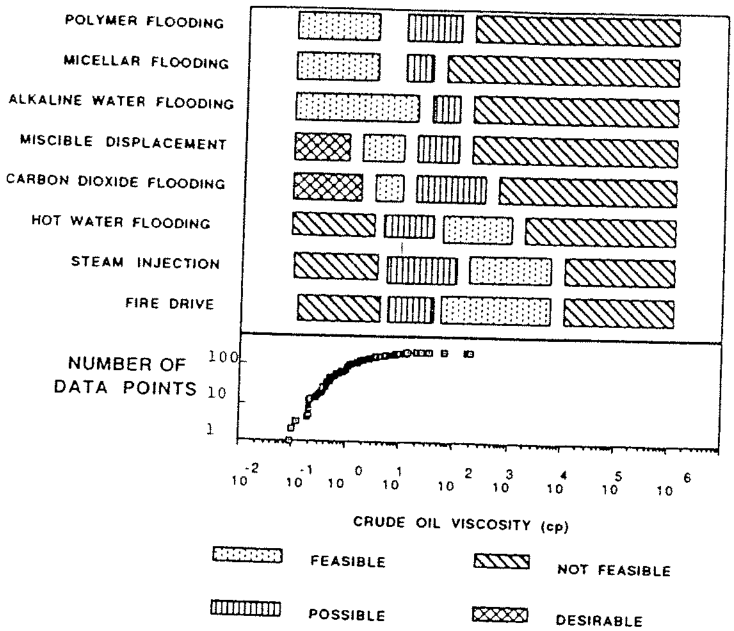

Figure 7. Saudi crude oil viscosity ranges for different E.O.R. methods.

Laboratory Design of any EOR Method Under Saudi Reservoir Conditions

The design of an EOR technique for a specific Saudi reservoir is basically related to the screening guides that can be developed as follows: The range of Saudi crude oil viscosity is from 0.1 to 10 centipoise as shown in Figure 7. The limits for Saudi porous medium

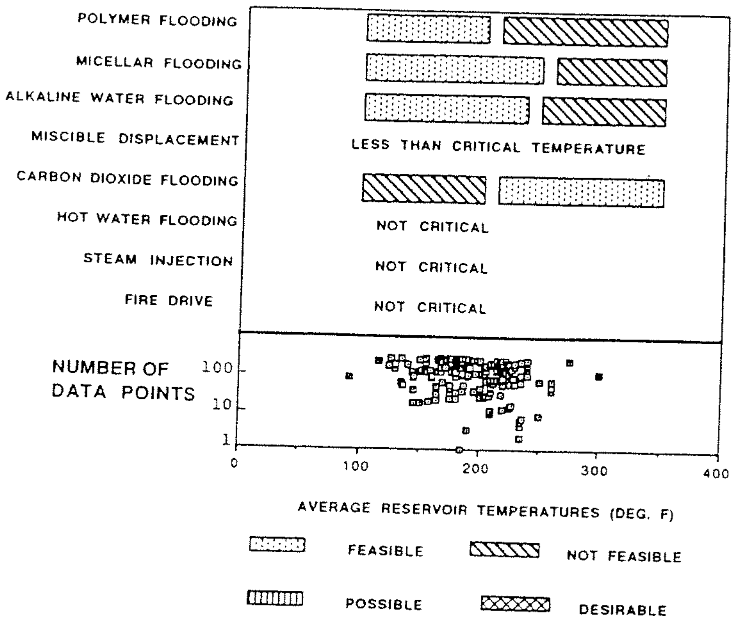

Figure 8. Average Saudi reservoirs temperature limitation for different E.O.R. methods.

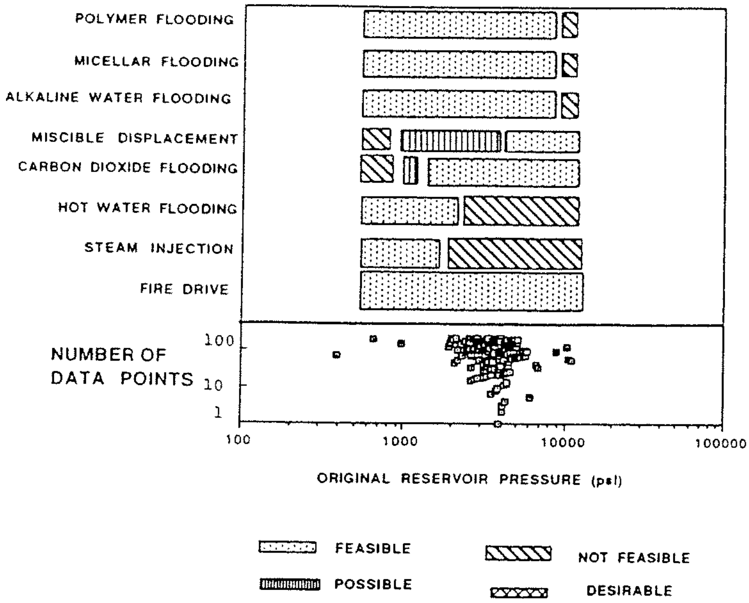

Figure 9. Original Saudi reservoirs pressure limitation for different E.O.R. methods.

permeability and porosity can be determined from Figures 12 and 13. These limits are from 1 to 1500 md for permeability and from about 10 to 30% for porosity. However, laboratory experiments have to be designed and carried out based on the actual reservoir conditions. Since there is considerable variation in porosity and permeability, the selection of the porous medium suitable for representing Saudi reservoir is not clear cut. The

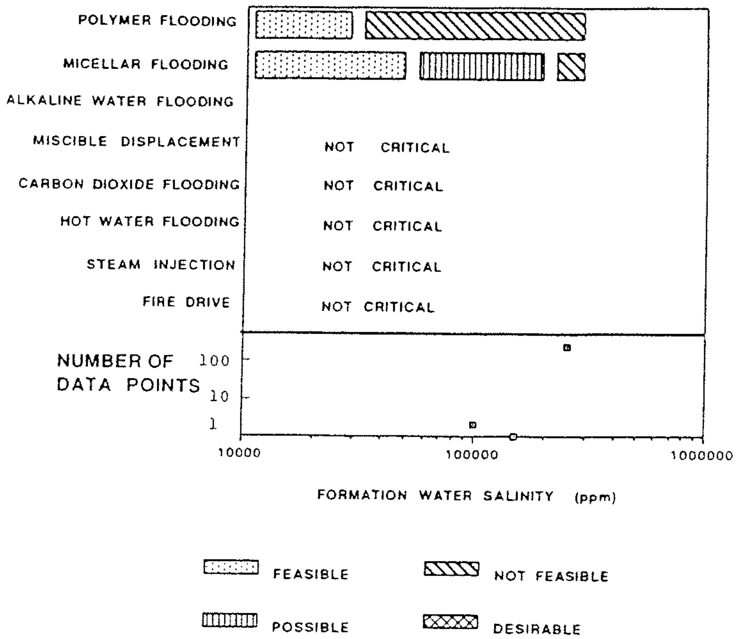

Figure 10. Feasibility of E.O.R. methods to Saudi formations water salinity.

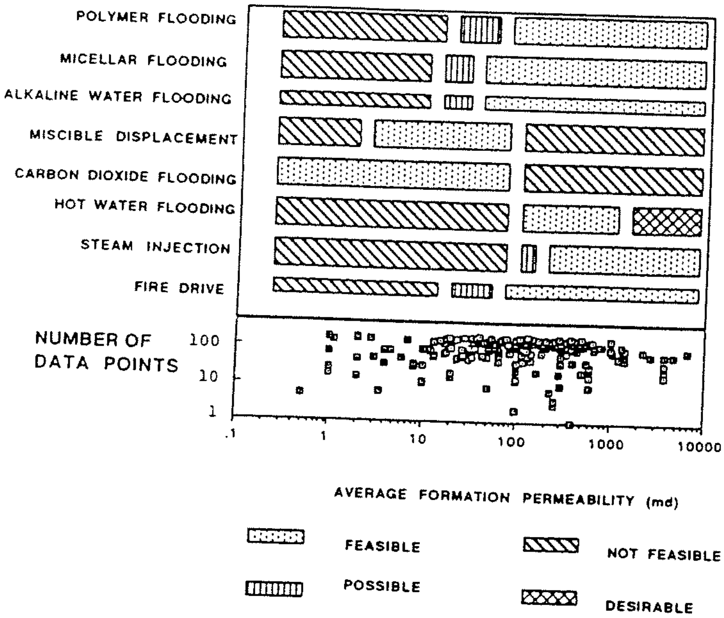

Figure 11. Saudi reservoirs formation permeability guides for applying E.O.R. methods.

connate water salinity conditions of Saudi reservoirs place some restrictions on the laboratory design of the EOR methods by chemicals. To ensure optimal displacement efficiency, the injected chemical solution slug must have an optimum salinity that gives minimum residual oil.

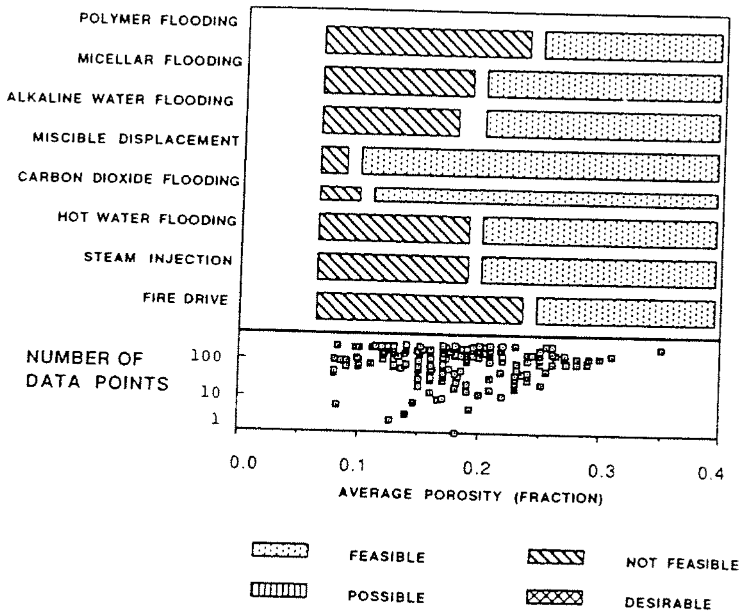

Figure 12. Saudi reservoirs formation porosity guides for applying E.O.R. methods.

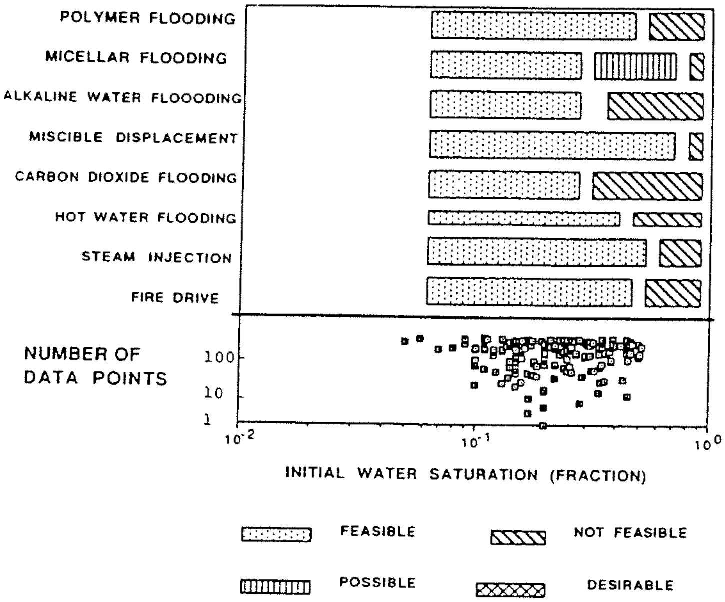

Figure 13. Initial Saudi reservoirs water saturation guides for different E.O.R. methods.

Economic Analysis

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 nature derived, others are controllable. Some of these factors are displacement efficiency, sweep efficiency, and economic factors.

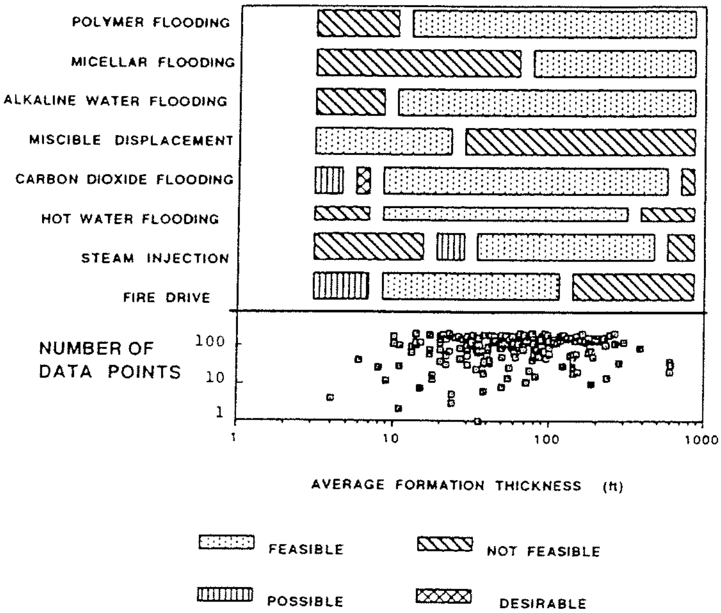

Figure 14. Feasibility of Saudi reservoirs formation thickness for E.O.R. methods.

Economic factors can overshadow physical ones in commercial oil production. Even if provisions are made to improve recovery by increasing displacement and sweep efficiencies, cost to accomplish this cannot be higher than added oil value. Considerable variables for any economic evaluation include estimated amount of oil recoverable, cost to conduct the operation, and price of the oil. The higher the crude price, the more feasible to recover oil from linear deposits using effective but costly methods (Geffen 1975). An investigation of the economical feasibility of the EOR methods that can be applied under Saudi reservoir conditions must be carried out.

Conclusions

Based on the screening analysis discussed in the present study for applying EOR methods to Saudi Oil fields, the following conclusions can be derived:

(1) The most suitable technical EOR methods applicable to Saudi oil fields are the miscible flooding processes using suitable gases, such as carbon dioxide and natural gases.

(2) Chemical flooding may be applicable but a new technology should be developed in order to be able to apply any of the chemical EOR methods.

(3) The laboratory work should be performed at reservoir conditions of pressure and temperature in order to obtain results that can be used in the actual engineering design of the selected EOR method. In addition, crude oil, formation water, and actual cores from the reservoir must be used.

(4) Variations of the thermal EOR methods may be effective in Saudi oil fields under special conditions.

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