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Development of an Expert System for EOR Method Selection

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Abstract

Non-conventional enhanced oil recovery (EOR) methods are expected to be applied in a number of Egyptian oil fields in the near future. Human expertise and the results of previous applications world wide are indispensable in the the decision-making process of selecting the most feasible EOR method. This paper presents the current development of a knowledge-based expert system for the selection of the EOR method in petroleum reservoirs. The development of this system involved the following stages:

1. Knowledge Acquisition: This has been achieved through a comprehensive literature review of the successful EOR recovery projects world wide coupled with experimental results from previous and current research activities at different research institutions and organisations. A new analysis method based on statistical evaluation has been used to produce the rules used in the expert system formulation.
2. System Formulation: The acquired knowledge from the first stage has been coded using a computer program. This involves the representation of the acquired knowledge through rules. These rules are divided into separate and identified groups in order to facilitate the search of the rules, and their removal from or addition to the knowledge base.
3. System Verification and Validation: This has involved the analysis of the consistency of stored knowledge and accurately reproduce the strategies used by experts and available in the literature to solve the problems of selection of EOR technique for different circumstances.

It is believed that with such a system an engineering judgment that stems from knowledge and experience will be available to sort, process, analyse and cross-refer the acquired reservoir data. Coupling this with other sources of information will allow us to achieve the most feasible selection of EOR techniques for Egyptian oil fields and allow for an efficient and profitable operation of oil reservoirs.

Introduction

The use of reservoir energy to produce oil and gas generally results in a recovery of less than 50% of the original oil in place depending on reservoir characteristics and the primary recovery mechanisms. A variety of supplemental recovery techniques have been developed to enhance the recovery factor obtained by utilising only the natural forces present in the reservoir. These supplemental recovery methods may be classified into conventional secondary recovery techniques - water injection and gas injection - and tertiary recovery methods such as miscible displacement, thermal recovery, and chemical flooding.[1] However, because some of these processes may be applied early in the life of a reservoir, the "tertiary" term is no longer appropriate. Therefore, the term "Enhanced Oil Recovery" (EOR) has been used to refer to the non-conventional oil recovery methods - other than waterflooding and gas injection - that give additional production resulting from the introduction of artificial energy into the reservoir.

Enhanced oil recovery (EOR) methods may be divided into two main categories: thermal and non-thermal displacement processes.[2] Thermal recovery methods include hot fluid injection methods (steam or hot water) and in-situ combustion (forward or reverse combustion) methods. Non-thermal recovery methods - or improved fluid-injection methods - may be divided into immiscible displacement processes (e.g. polymer and surfactant flooding) and miscible displacement processes (e.g. microemulsion flooding, $C0_2$, and miscible gas injection). **Fig. 1** shows a flowsheet of the different conventional, non-conventional, and possible future recovery processes.[3] Microbial flooding has recently gained increased recognition as one of the promising EOR methods.[4,5,6]

Generally, thermal recovery methods fits reservoirs containing heavy oils with very high viscosity. Thermal methods - together with processes based on injection of gases such as carbon dioxide, nitrogen, *etc.* at sufficiently high pressure to obtain miscibility with the reservoir oil - reduce the viscosity of crude oils to improve mobility ratios.[7-10] Miscible displacement methods based on gas injection are also applicable in reservoirs containing lighter oils.[11]

Chemical waterflooding methods are mainly used for relatively light oil reservoirs. Polymer flooding employs polymers like polysaccharides and polyacrylamides which are capable of increasing water viscosity resulting in improved mobility ratios and better oil displacement.[12] Surfactant flooding employs surfactants capable of reducing interfacial tension between oil and rock and between oil and displacing water.[13] Microemulsion and micellar flooding use surfactant mixed in water, hydrocarbon, and co-surfactants at concentrations high enough for the surfactant molecules to cling together to form micelles which can solubilise or dissolve the reservoir oil by entrapment of tiny oil droplets into the centre of the micelles causing miscibility.[14] In alkaline waterflooding, reaction between the alkaline solution with certain organic acids present in crude oils results in the formation of surfactants, which enhance emulsification as a result of the reduction of the interfacial tension.[15] The rock wettability may also be altered by the reaction of the alkaline solution with the reservoir rock. The wettability change results in an increase of oil recovery because the water wetness of the rock increases.[16]

A number of oil fields in Egypt are expected to undergo one or more of these EOR methods in the near future. However, the implementation of any of the EOR methods involves huge capital expenditure. Since crude oil recovery by EOR processes is a rather difficult and high risk operation, the proper selection of the EOR method for any particular reservoir is necessary to achieve a successful and profitable project.

Numerous parameters should be carefully studied in order to asses the applicability of various EOR methods. These include reservoir depth, pressure, temperature, rock type, thickness, porosity, permeability, crude oil type, oil gravity, oil viscosity, water salinity, *etc.* Therefore, the problem faced by the reservoir engineer is to identify all the EOR methods applicable to the candidate oil field and select the most appropriate method based on technical and economic criteria. This problem of selecting the most suitable EOR process has created a crucial need for experts to help, sort, process, analyse and cross-refer the acquired reservoir data coupled with other sources of information to achieve the most feasible selection of EOR technique to be applied in candidate oil fields in an efficient and profitable way.

In spite of the active research work in the area of EOR Egypt during the past decade[17-22], the Egyptian petroleu industry has very limited experience in actual fie applications of EOR. Scarcity of previous field experienc coupled with the fact that only very few experts, world-wid know about all EOR processes that are available ha prompted the current development, of a knowledge-bas expert system that can facilitate the reservoir engineer's task selecting the most appropriate EOR method.

In this paper, the details of the developed EOR expe system are presented. The paper also describes the quantitati probabilistic approach used in the evaluation of successf field data in order to produce the production rules used in th expert system formulation.

Expert System

Expert systems, also called knowledge-based systems, ar computer programs which provide expert advice. Thei purpose is to simulate the reasoning of a human expert in well-defined field of knowledge. This fairly limited field i called knowledge domain. Expert systems can solve some o the same problems and give advice about some of the sam situations for which an expert would normally be hired.[23]

The Expert system program contains three parts: a data structure which represents the human expert's knowledge; algorithms to manipulate the data structure (sometimes referred to as inferencing); and a user friendly interface to request input from the user and present expert system results.[24]

The main advantages of expert systems are that artificial expertise is permanent, the knowledge transferred is concise and inexpensive, artificial expertise is easier to document than human expertise, and finally, expert systems are able to raise the average performance of human experts by incorporating the knowledge of more than one expert.[25]

Expert system technology has recently gained an increasing importance in the petroleum industry. Application areas include diagnosis, planning, design, prediction, interpretation, monitoring, debugging, repair, and control of different processes in oil and gas engineering. Some of the better-known expert systems applications in the petroleum industry include: well log analysis[26,27], drilling[28,29], well stimulation[30,31], rod pumping[32,33], well testing[34,35], metering[36], simulators' input data preparation[37], oilfield development[38], enhanced oil recovery[25,39], *etc.*

EOR Expert System Development

The development of the EOR expert system to select the most suitable EOR method involves the following three phases: knowledge acquisition, system formulation, and system verification and validation.

1. Knowledge Acquisition:

The first activities carried out at the beginning of this phase were basically aimed at the identification and delimitation of the domain as well as the identification of experts. These tasks have been achieved through a comprehensive literature review of the successful EOR recovery projects world wide coupled with the evaluation of the experimental results from previous and current research activities at Cairo University and other research institutions and organisations.

Many screening guides have been suggested for the application of EOR methods.[3,8,40-47] The screening guides are mainly based on experimental results, qualitative interpretation of field results and authors' experience. These screening guides, however, show some discrepancies which may be attributed to the subjective interpretation of the data and delineation of the applicability ranges of different EOR methods.

In this study, a quantitative approach is to be implemented to develop a more objective screening guide for EOR methods. The data used in the analysis are the technically successful and economically profitable EOR projects world-wide.[48] The number of reported successful and profitable field implementation of EOR processes used in the analysis is 421 projects out of 456 reported in the survey. Their distribution among the various EOR methods is shown in **Fig. 2**. It is clear that steam flooding accounts for about half of the total number of the projects. Only two successful field applications have been cited for surfactant, micellar-polymer, and microbial floodings, and three field applications for alkaline flooding.

The main parameters affecting the selection of the most suitable EOR process include some reservoir condition parameters as reservoir depth, original oil in place, initial oil saturation, reservoir pressure, and reservoir temperature; reservoir rock characteristics as reservoir rock type, reservoir porosity, reservoir permeability, pay zone thickness, swelling clay content, dipping angle, well-to-well communication and connate water saturation; and finally reservoir fluid characteristics as oil type, API gravity, oil viscosity, water salinity, and acid number.[3,8,40-47]

Only six parameters have been used in the quantitative analysis; namely API gravity, oil viscosity, porosity, permeability, reservoir temperature and formation depth. The rest of the parameters are either not reported in the survey[48] (e.g. formation thickness and formation water salinity) or has no quantitative nature (e.g. formation type. and clay content). The quantitative analysis of all parameters for each EOR method followed the following steps:

- Constructing a diagram showing the distribution of the various successful projects over the parameter range for each EOR method. For example, **Fig. 3** shows the distribution of steam flooding projects with respect to the API gravity while **Fig. 4** shows the distribution of hydrocarbon miscible projects with respect to oil viscosity.
- Determining the minimum (X_{min}) and maximum (X_{max}) values for each parameter associated with the application of a successful EOR method.
- Calculating the arithmetic average $\overline{X}$ and standard deviation (σ) values of each parameter (API gravity, viscosity, etc.) for each EOR method.
- Dividing the entire domain of each parameter into three regions: Feasible, Possible, and Infeasible **(Figs. 3 and 4)**. The boundaries between the different regions were selected on the basis of the previously calculated statistical values as follows:
  - * Feasible region: extends from $\overline{X} - \sigma$ to $\overline{X} + \sigma$ for each parameter.
  - * Possible region: extends from X_{min} to $\overline{X} - \sigma$ and $\overline{X} + \sigma$ to X_{max} for each parameter.
  - * Infeasible region: covers the parameter's domain not covered with the feasible and possible regions.

The standard deviation value was selected as a basis for defining the boundaries of the feasible region because it is one of the simplest parameters for measuring the dispersion of the data, and because it has the property that 68.27% of the cases (i.e. successful and profitable field applications) are included in the range of $\overline{X} - \sigma$ to $\overline{X} + \sigma$.[49] Therefore, the feasible region can be considered as a good reflection of the optimum range of the parameter for the application of any EOR process.

It should also be mentioned that the boundaries of the different regions were slightly modified to incorporate the previous research experience. This mostly applies to chemical waterflooding and microbial flooding methods due to the scarcity of field applications.

The developed screening criteria for different EOR methods are graphically displayed in **Figs. 5-10**. They represent the knowledge base to be later formulated and implemented in the developed EOR expert system.

2. System Formulation:

The system formulation involves the representation of the acquired knowledge from the first phase through rules. The rules are conditional statements in the form of IF-THEN statements. These statements use the assigned numeric values (boundaries from the developed screening criteria) or linguistic values (e.g. sand/carbonates for the type of formation, or yes/no for high or low formation water salinity or clay content) of the different parameters to determine the goals of the expert system. These rules are divided into separate and identified groups in order to facilitate the search of the rules, and their removal from or addition to the knowledge base. An extract of coded rules of the EOR expert system is shown in **Fig. 11**.

The expert system program was written using PROLOG (PROgramming in LOGic) language. Unlike other Programming languages, e.g. FORTRAN, BASIC, *etc.*, PROLOG programs give the computer a description of the problem using a number of facts and rules, and then asks it to find all possible solutions to the problem. In addition, in programming using FORTRAN, BASIC, *etc.*, the programmer must tell the computer exactly how to perform its tasks while once the PROLOG programmer has described what must be computed, the PROLOG itself organises how the computation is carried out.[50]

The developed EOR expert system has been designed to run in one of two modes. In the first mode, the desirable goal is to determine the technical feasibility, possibility, and infeasibility of the application of EOR methods to a particular reservoir. In the second mode, the desirable goal is to conclude the most suitable EOR method to a particular reservoir and calculate the confidence factor for such conclusions.

For the first mode, the EOR method is evaluated to be *feasible* if all values of the different parameters are within the feasible region. On the other hand, if only one of the parameters is within the infeasible region, the EOR method is evaluated as *infeasible*. If some of the parameters are in the feasible region while the rest are in the possible region, the EOR method is evaluated as *possible* for application.

The second mode is much more useful which internally evaluates each EOR method based on the values of different parameters as *possible or infeasible*. The possible methods are then re-evaluated for assigning a value for the confidence factor. The method with highest value of the confidence factor is selected as the most suitable EOR method to the particular reservoir. A simple method is currently being implemented based on the number of parameters within the possible and feasible regions. However, more sophisticated methods based on template matching technique (using vector representation of the knowledge base) and Heuristic approach, previously used in expert system development for multiphase flow rate measurements[51], are currently under investigation.

Finally, the system has a user-friendly interface which allows data input as well as the option to load, list, edit, erase, update, save, and consult the knowledge base. Editing, erasing, and updating the knowledge base is only accessible to authorised expert users.

3. System Verification and Validation:

This phase has involved the analysis of the consistency of stored knowledge and accurately reproduce the strategies used by experts, that are available in the literature[39,48] to select the most suitable EOR process.

EOR Expert System Utilisation

The developed EOR expert system could be utilised to determine the most feasible EOR method for a particular reservoir based on the available reservoir fluid and rock data. Laboratory studies and/or computer simulations are essential to verify the technical feasibility of the selected EOR method. It is clear that with the availability of the developed EOR expert system, laboratory and/or computer runs will be mainly directed towards studying the sensitivity of some design parameters rather than completing the evaluation of all the EOR methods under numerous design and field conditions.

If the runs prove the technical feasibility of the selected EOR method, an economical evaluation should be performed. Engineering designs for the application of a pilot field test are then initiated if the economical evaluation shows that the selected EOR method is economically feasible. In the case of either technical or economical infeasibility of the first selected EOR method, the expert system should be checked for the second best EOR method. **Fig. 12** shows a schematic diagram for the utilisation of the developed EOR system.

EOR Expert System Applications

Some of the Egyptian oil reservoirs are considered to be good candidate for applying a certain type of various EOR technique. By using this new developed expert system, it was found that the most suitable technical EOR methods applicable to Egyptian oil reservoirs are the miscible flooding processes using suitable gases, such as carbon dioxide and nitrogen. Also, chemical flooding methods can be applied in number of the Egyptian oil reservoirs taking into consideration the salinity parameter.

Future Work

The current knowledge base in the developed EOR expert system will be continuously updated to include new field data and/or experimental results. The new data will give better and more accurate delineation of the boundaries in the various parameter domains, representing the range of applicability of EOR application. Other statistical parameters could also be evaluated for better and more objective representation of the application limits for various EOR methods.

The reservoir characteristics of the different oil producing formations will be collected to investigate and select, using the developed EOR expert system, the most technically feasible EOR method to each particular reservoir.

More sophisticated pattern recognition techniques, based on template matching technique (using vector representation of the knowledge base) and Heuristic approach, are to be implemented for better evaluation of the confidence factor and consequently selecting the most appropriate EOR method. An investigation of the possibility of ranking the different parameters or assigning a weighting factor for each of them based on the usefulness in determining the most suitable EOR method will be also investigated.

Finally, the expert system could be extended to predict the expected increase in oil recovery based on statistical analysis of results from previous successful field projects or laboratory experiments. These predicted figures coupled with available or developed economic models could be used.

Conclusions

1. The application of the emerging expert system technology to EOR method selection is very important and useful.

2. Three phases were essential for the development of the EOR expert system. These are knowledge acquisition, system formulation, and system verification and validation.

3. A new quantitative statistical approach has been used to develop the objective screening criteria based on the analysis of the successful EOR projects world-wide.

4. The core of the EOR expert system is the conditional rules based on our developed objective screening criteria for EOR methods.

5. The developed system, implemented in PROLOG, has two different modes which allow either the determination of the technical feasibility of the EOR method or the selection of the most suitable EOR method.

6. It is believed that with such a system an engineering judgement, that stems from knowledge and experience, is available. The most feasible selection of EOR technique, to be applied in Egyptian Oil fields in an efficient and profitable operation of oil reservoirs, has been established.

Nomenclature

CO_2	=	Carbon dioxide
EOR	=	Enhanced Oil Recovery
HC	=	Hydrocarbon
H	=	Resevoir depth, ft
K	=	Permeability, md
$PROLOG$	=	PROgramming in LOGic
T	=	Resevoir temperature, ^{O}F
X	=	Arithmetic mean
X_{min}	=	Minimum parameter value
X_{max}	=	Maximum parameter value
μ	=	Oil viscosity, cp
ϕ	=	Porosity, %
σ	=	Standard deviation

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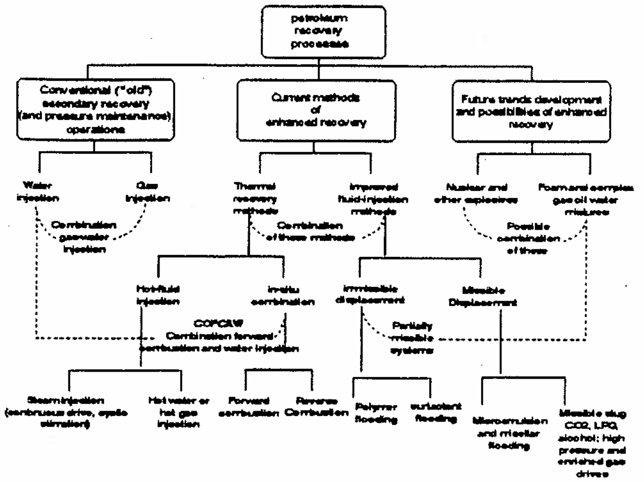

Fig. 1-Classification of EOR recovery processes. (Ref. 3)

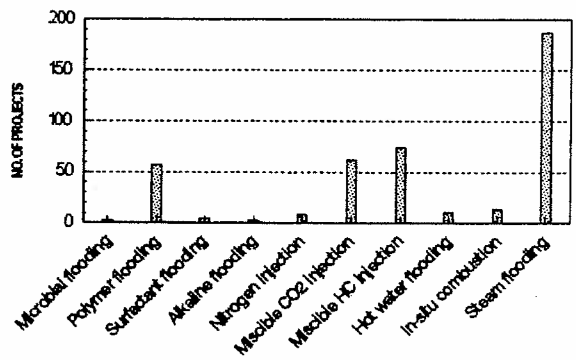

Fig. 2-Distribution of succsessful EOR projects.

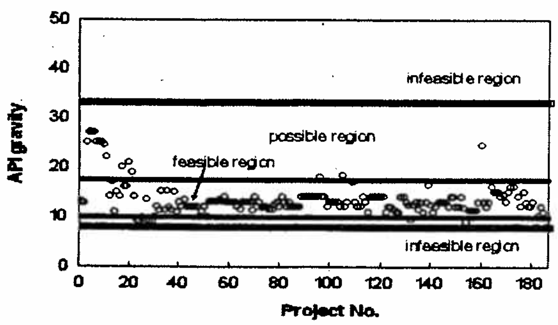

Fig. 3-Distribution of steam flooding projects with respect to API gravity.

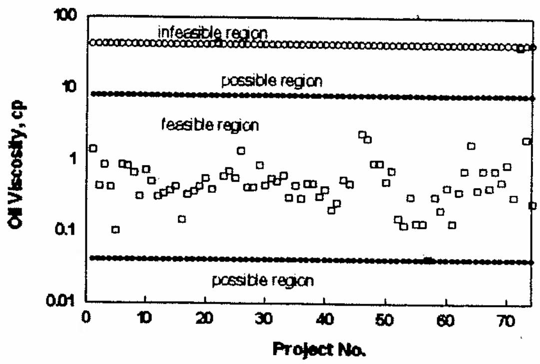

Fig. 4-Distribution of miscible HC projects with respect to oil viscosity.

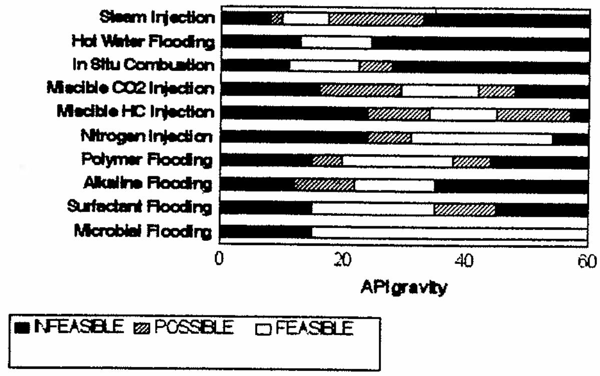

Fig. 5-API gravity ranges for different EOR methods.

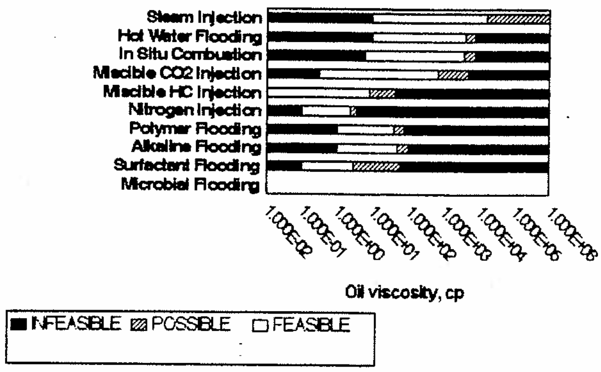

Fig. 6-Oil viscosity ranges for different EOR methods.

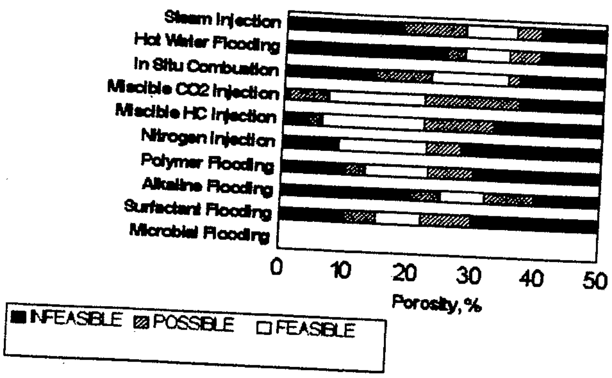

Fig. 7-Porosity ranges for different EOR methods.

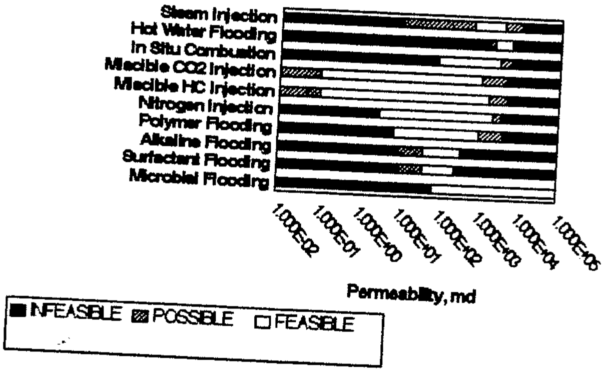

Fig. 8-Permeability ranges for different EOR methods.

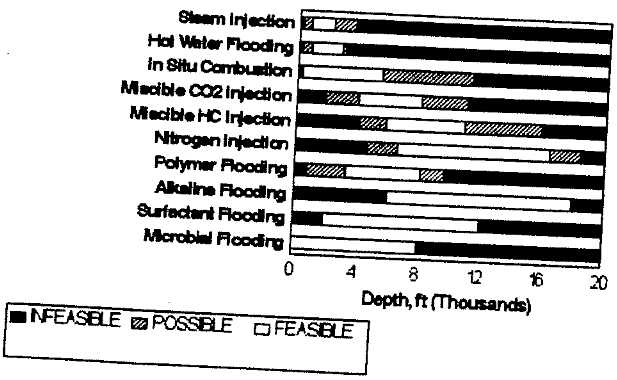

Fig. 9-Depth ranges for different EOR methods.

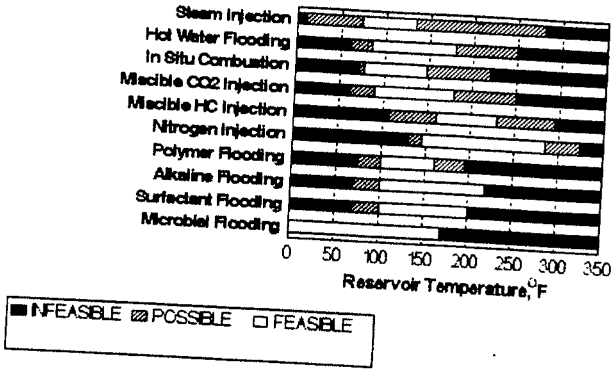

Fig. 10-Resevoir temperature ranges for different EOR methods.

```
rule(1,"steam injection","feasible",[1,2,3,4,5,6])
rule(2,"steam injection","possible",[7,8,9,10,11,12])
rule(3,"steam injection","infeasible",[13,14,15,16,17,18])
cond(1,"API >= 10 and API <=17.5")
cond(2,"T >= 70 and T <=135")
cond(3,"ϕ >= 28 and ϕ <=36")
cond(4,"K >= 620 and K <=3800")
cond(5,"H >= 750 and H <=2150")
cond(6,"μ >= 10 and μ <=400000")
cond(7,"API >= 7.5 and API <=10 OR API >= 17.5 and API <=33")
cond(8,"T >= 10 and T <=70 OR T >= 135 and T <=280")
cond(9,"ϕ >= 18 and ϕ <=28 OR ϕ >= 36 and ϕ <=40")
cond(10,"K >= 10 and K <=620 OR K >= 3800 and K <=10000")
cond(11,"H >= 200 and H <=750 OR H >= 2150 and H <=3600")
cond(12,"μ >= .01 and μ <=10 OR μ >= 400000 and μ <=5000000")
cond(13,"API >= 33 and API <=7.5")
cond(14,"T >= 280 and T <=10")
cond(15,"ϕ >= 40 and ϕ <=18")
cond(16,"K >= 10000 and K <=10")
cond(17,"H >= 3600 and H <=200")
cond(18,"μ >= 5000000 and μ <=0.01")
```

Fig. 11-An extract of the coded rules of the EOR expert system.

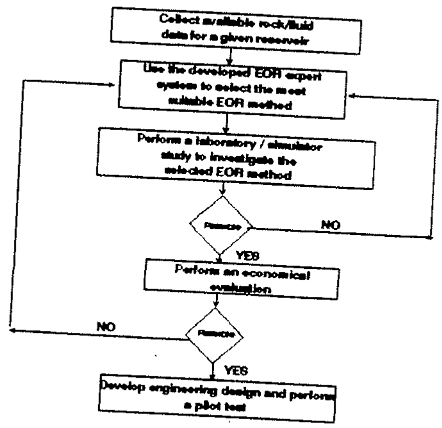

Fig. 12-EOR expert system utilisation.