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TITLE AN EXPERT SYSTEM FOR SCREENING ENHANCED OIL RECOVERY METHODS

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AN EXPERT SYSTEM FOR SCREENING ENHANCED OIL RECOVERY METHODS

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ABSTRACT

Many potential users argue against using expert systems for solving problems. The two main reasons for this argument are (1) the relatively high cost of specialized LISP Machines and the large expert system shells written for them, and (2) some expert systems are used for jobs that the average professional could do with a relatively short literature search, a few hours of reading, and a few calculations. This paper demonstrates how a small expert system can be written with inexpensive shells (CLIPS and EXSHELL) and run on inexpensive personal computers. CLIPS is a forward-chaining rule-based system written in the C language. Rules are entered in a LISP-like format. EXSHELL is a backward-chaining rule-based system written in the PROLOG language. These shells were used to write a small expert system, an expert assistant, which is used to help petroleum engineers screen possible enhanced oil recovery candidate processes. Though the final candidate process is selected on the basis of an economic evaluation, the expert assistant greatly reduces the amount of work involved. Rather than having to do exhaustive economic calculations for all possible processes, the work is reduced to an economic comparison between two or three candidates. Rather than having to glean information and data from graphs or charts in technical papers, the user and the

system work interactively to obtain the needed information. The system selects the optimal collection of paths to the solutions and is easily updated as new data become available. This paper also demonstrates the utility and ease of use of these inexpensive shells, compares the approach used by each, and demonstrates the relative advantages of forward-chaining versus backward-chaining for this problem.

INTRODUCTION

Some of the reasons to study enhanced oil recovery (EOR) are listed in a 1986 paper by Stosur (1). At the time his paper was printed, only 27% of the oil ever discovered in the United States had been produced. Under current economic conditions about 6% more will be produced using existing technology. This leaves the remaining 68% as a target for EOR. Currently, only about 6% of our daily oil production comes from EOR. These numbers indicate that, even in these times of reduced awareness of an impending energy crisis, the study of EOR can be rewarding because of the high potential payoff.

EOR is expensive. It is necessary for engineers to pick the best EOR method for the reservoir in question to make or optimize profits. The entire screening method is expensive and typically involves many steps. The first step is to consult the technical screening guide. Screening guides consist of a table or several charts that list the rules of thumb for picking the proper EOR technique as a function of reservoir and crude oil properties. The candidate techniques are often subjected to laboratory flow studies. Data from these studies are often used to demonstrate the viability of the selected technique. Economic evaluations are usually carried out throughout the screening process.

Our expert assistant was developed to replace the tables and graphs presented in the technical screening guides and computerize this part of the screening process. The expert assistant provides essentially the same information as the old table and graph method, but it is more comprehensive than the tables and is easier to use than the graphs. At the end of each session, it provides the user with a weighted list of potential techniques. Developing such a list is difficult to do with the tables. The expert assistant is user friendly; it asks all the questions and leads the user through the first stage of the screening process. Although the final choice of a technique will be based upon economics, the first screening step is quite important because of the high cost of going through all the steps of the screening process and determining and choosing the most economically optimum EOR technique.

A prerequisite for our expert assistant was to make it easily available to several users. So rather than use our sophisticated hybrid expert system shell and LISP machine, we used expert system shells that were inexpensive and designed to run on a PC. It was then a simple matter for users to request a floppy disk containing the shell and the expert system. With a few instructions they could be "in business" with this user friendly expert assistant.

THE PC-BASED EXPERT SYSTEM SHELLS

We felt fortunate to find two inexpensive PC-based shells CLIPS (2) and EXSHELL (3) that were adequate for our expert assistant.

CLIPS was developed by NASA. It is a forward-chaining, rule-based shell written in the C programming language, which emulates the LISP programming Language. To program with the CLIPS shell, it is helpful, though not essential, to know both the C and the LISP programming languages.

EXSHELL was developed by the University of New Mexico Computer Science Department. It is a backward-chaining, rule-based shell written in the PROLOG programming language. One must know some PROLOG in order to program with EXSHELL.

Both of these shells are valuable tools, even though they have different features. One significant result of our study is that the comparisons of the shells and the programs may be useful to other investigators in the future. For this reason we have included a section on program comparisons.

Even though our expert assistant is not large, compared with some expert systems, it does use over 300 rules. Both shells handle this expert system easily and it appears that neither will have any trouble as new rules are added in the future.

THE EOR SCREENING PROBLEM

For this study we define EOR as any technique that goes beyond water flooding or gas recycling to increase oil well production. This includes the injection of materials not usually found in the reservoir. The expert assistant we have developed relies mainly on the work of Taber and Martin (4) and Goodlet et al. (5,6) for its rules.

Enhanced oil recovery processes may be divided into four general categories: thermal, gas injection, chemical flooding, and microbial. Thermal techniques may be further subdivided into *in situ* combustion and steam flooding. To be technically and economically feasible, thermal methods must be applied in reservoirs with fairly high permeabilities. Steam flooding is the EOR method that accounts for the highest daily production in the US at present. Traditionally, steam flooding has been applied to relatively shallow reservoirs containing heavy, viscous oils and this traditional use of the method is reflected in the screening criteria used for the expert systems developed here. Recently, however, studies and field tests have indicated that steam injection may be attractive in deeper reservoirs containing lighter, less viscous oils. One of the advantages of an expert system over the compilations of charts and graphs of present day screening guides is that the expert system may be modified by changing a few program steps to reflect advances in our understanding of technology. Thus, we could modify the expert systems presented here to reflect the development of steam flooding in light oil reservoirs when an expert in that technology becomes available to us, without changing other information already resident in the program.

Miscible gas injection techniques are, in a sense, the opposite extreme to steam flooding. For these methods to be feasible, the reservoirs must have considerable depth so that the process pressure is adequate for achieving miscibility between a displacing fluid and the displaced fluid. However, the reservoir permeability is usually not a critical factor and it is easier to generate miscibility in light oils. Miscible gas injection may be subdivided into hydrocarbon, nitrogen and flue gas, and carbon dioxide injection. And similarly to new developments in steam flooding, there has been a considerable development of immiscible gas flooding technology since the screening guides used for the rules for our expert systems were presented. Likewise, when an expert in immiscible gas flooding becomes available to us, we can easily modify our programs to reflect this new knowledge.

Chemical flooding may be divided into polymer, surfactant-polymer, and alkaline flooding. With chemical flooding, feasibility imposes some restrictions on reservoir permeability. But more often, reservoir characteristics such as temperature, formation brine and rock composition, which affect the chemical stability, are the limiting parameters.

Miscrobial techniques are relatively new and primarily experimental at this time and thus were included for completeness. We did not subdivide this category. Figure 1 illustrates the EOR categories and subdivisions, or EOR methods, as the search tree for the expert assistant.

We often hear this comment: "We have excellent papers on this subject with graphs and tables and information to help us solve the problem. Why do we need an expert system?" Although you don't absolutely need an expert system for this problem, you can solve it more quickly, and often better, with one. Table 1 (from Ref. 4) is a matrix of eight EOR techniques and nine EOR criteria.

Theoretically, if engineers know the values of the EOR criteria for the reservoir in question, they should be able to pick some candidate processes from Table 1, even if they know very little about the subject of EOR. Some simple examples will show some of the problems with this argument. For Example 1, we will use the following EOR criteria with Table 1:

(1) Gravity = 18 deg API
(2) Viscosity = 500 cp
(3) Composition = high percent C_4 - C_7
(4) Oil Saturation = 50%
(5) Formation Type = Sandstone
(6) Payzone Thickness = 35 ft
(7) Average Permeability = 1000 Md
(8) Well Depth = 2000 ft
(9) Temperature = 110°F

If we search the table by starting at the top and moving left-to-right before moving down a row, we are using the backward-chaining or goal-driven method. With this method, we first assume a solution, e.g., hydrocarbon gas-injection, then check the data either to verify or to disprove that assumption. With the data-driven or forward-chaining approach, the search would begin in the upper left-hand corner of the table and move down row by row to the bottom before moving to the next column. Thus, the search would start with the datum value for the oil gravity and check that value against every EOR method before moving on to the other data. In this example we use backward-chaining to find that steam flooding is the only good method to use for this case. The results of this search are shown in Fig. 2. Although it is possible that *in situ* combustion techniques would also work, it is not perfectly clear what is meant, in Table 1, by "greater than 150°F preferred."

This situation is not ideal because we have only one candidate method for the next screening step. This candidate method could be eliminated, for other reasons, in a later screening step, and we would then have no candidate recovery methods for this case. Having a reservoir that is not recommended for EOR is certainly legitimate. But we should not eliminate the possibility because of too little knowledge. If we change our example just a little, we can have the opposite problem. Example 2 has the following values for the EOR criteria:

(1) Gravity = 35 deg API

(2) Viscosity = 10 cp

(3) Composition = high percent C_4 - C_7 and some organic acids

(4) Oil Saturation = 50%

(5) Formation Type = Sandstone

(6) Payzone Thickness = 10 ft

(7) Average Permeability = 1000 Md

(8) Well Depth = 5000 ft

(9) Temperature = 150°F

If we search Table 1 again with a backward-chaining technique, we obtain the results shown in Figure 3. This time only one potential EOR method, steam flooding, has been eliminated. Thus, we go to our second step with possibly too many candidates.

This is not a criticism of Ref. 4 or of tables like Table 1. In fact, for every case like the examples above, there are several that will fall in between these extremes. It is merely an effort to point out that we will often need more information than is available in these tables to do a good first screening step. Much of the information is available in Refs. 4, 5, and 6. References 5 and 6 also have Tables similar to Table 1. Table 2 contains all of the material from Table 1, as well as some of the information from the table in Ref. 6, including another EOR method, microbial drive. Although this additional information helps to improve the results of our search, we still need more information on the impact of a formation temperature of 110°F when a temperature greater than 150°F is preferred. We need information that will help us rank two or more methods when they all fall within the acceptable range. What we need from this screening step is a ranked list of methods. A ranked list can be obtained, even by a nonexpert, by reading the papers and, in some cases, by conducting a short literature search in addition to using Table 1 or 2. The time invested by the nonexpert in this screening step is now greater than just the few minutes required for searching the tables. If the exercise has to be repeated several times or by several different nonexperts, a small PC-based expert system can easily be justified for this job.

Figures 4-14 demonstrate the basis of our scoring system for the various EOR criteria and EOR methods. Figures 5, 11, and 12 were taken from Ref. 4 and modified. The others were created by studying Refs. 4-9. Figures 4-14 show the relative influence of each of the EOR criteria on each of the EOR methods. Our scoring system is empirical, and it is designed to add some of our qualitative judgements, based on our expertise, to the expert system. The scoring system is based on the key words in Figs. 4-14, and works as follows:

Not Feasible	-50
Very Poor	-20
Poor	0
Possible	4
Fair	6
Good	10
Not Critical	12
Preferred	15

Note that *Not Critical* is a very good situation to have.

For the microbial drive method, the affect of viscosity, and to a large extent, porosity, are unknown. Until we have more information, we are assigning a score of 6 for an Unknown (the same as the grade for a Fair).

As an example of the scoring system, turn to Table 5 and consider an oil with a viscosity of about 500 cp. The hydrocarbon gas injection, surfactant-polymer, and alkaline chemical flood techniques are all Poor and all score zeros. The other two gas injection techniques, nitrogen and flue gas and carbon dioxide, are both Fair and each gets a score of 6. The polymer flooding technique cannot be used with a viscosity this high, so it gets a score of -50. Each of the thermal techniques is Good and each gets a score of 10. The microbial drive method has an Unknown, so it gets a score of 6.

Some of the EOR criteria carry more weight than others, and in some cases, a given criteria may affect one method more than another. In the program, the scores listed above have been adjusted slightly up or down to reflect these differences. Score adjustments have also been made in these cases. Much of the relative scoring and many of the adjustments to these scores have been made on the basis of experience and judgement. They were also influenced by a study of the more than 200 enhanced EOR projects listed in Ref. 9. The scores are listed in the program and can easily be changed by someone with different experience or with new information.

An important task of the expert system is to give the user meaningful advice about the individual EOR methods based on the raw scores computed by the program. For the CLIPS programs, we designed a system that produces numbers that are similar to the confidence factors found in many shells, including EXSHELL. The scores are computed on the basis of a maximum possible score of 100% for the best possible process. The best possible process is steam flooding. Thus, if all of the methods were to receive the best possible score they could get, steam flooding would get the highest, with 148 points. This method has the highest number of "Preferred" ratings in Figs. 4-14. The other EOR methods, with the exception of microbial drive, are all quite close. The raw score of 148 corresponds to 100%. All raw scores are divided by 148 to produce their relative confidence factor.

At the end of a session, the scores are tallied. The user now has a ranked list of candidates to take to the next screening step. So far, this approach has given realistic results. We have run these expert systems, with much of the information given in Ref. 9, for actual EOR projects. In about 60% of the cases run, the method ranked highest by the expert system was the method used by that project. In most other cases, the actual method used was ranked in the top three by the expert system. This is not too unusual because these data did influence the scores used by the expert system. That's the way expert systems are built. We keep comparing the results of the expert system with the results given by the experts and keep modifying until it is as good as the experts. This approach gives us confidence in the results predicted by our expert system. This approach is data-driven or forward-chaining, as opposed to the goal-driven or backward-chaining technique, which works well when using data given in the form of Tables 1 and 2. For this reason we built expert systems using both the forward-chaining and the backward-chaining modes, as will be discussed in the next section.

THE EXPERT ASSISTANTS -- HOW THEY WORK

If engineers were solving the EOR screening problem by hand, using the backward-chaining or goal-driven method, they would first pick a goal (e.g. the hydrocarbon gas injection method) from the left-hand side of

Tables 1 and 2. The engineers would then pick subgoals that must be met before the original goals could be satisfied (e.g., the gas injection category). The selection of subgoals would go on as long as necessary. In our case, we have only one subgoal, so it would stop here. The engineers would ask only those questions that are necessary to determine whether gas injection is a feasible category. When the gas injection category was established, the engineers would ask only those questions necessary to determine whether the hydrocarbon method would be feasible. If not, another goal would be picked. If yes, the problem will be solved unless more than one solution is desired. In this case, another goal is picked and the process is continued. The PROLOG-based EXSHELL works this way, with the PROLOG language doing much of the program control.

With the forward-chaining or data-driven approach, the engineer lets the data help find the way through the search tree. The system keeps asking questions until it is clear which node to move to next. The CLIPS shell is designed to work in this manner. CLIPS can also be programmed to do backward-chaining, but it normally requires more programming steps than forward-chaining. In either case, the programmer has more responsibility for program control than does the EXSHELL programmer.

Our first EOR expert assistant was written with CLIPS and with forward-chaining. The approach is to first find an acceptable EOR category from the list (chemical flooding, gas injection, thermal, or microbial) by asking for the values of the three EOR criteria that best delineate the categories (permeability, well depth, and viscosity). A category score is computed on the basis of average category scores represented by Figs. 5, 11, and 12. If the category score is less than a preprogrammed threshold value, the entire category is eliminated from further consideration.

The program then goes to the first acceptable category and tries to eliminate individual methods with the questions about oil temperature, gravity, and composition. The category methods are individually scored at this point. If the score is less than a second preprogrammed threshold, it is eliminated from further consideration. If all of the category methods are not eliminated at this point, the program goes on to ask questions about the salinity, and the remaining reservoir properties and the methods are scored further.

The program checks to see if there are any more acceptable categories to investigate. If there are, it repeats the process just described.

If there are not, it stops and prints the scores of the remaining candidate methods. A flow diagram for this version of the expert assistant is given in Fig. 15.

The first backward-chaining expert assistant was written with EXSHELL. This program works basically with Table 2, with several modifications from Figs. 4-14. The approach is to first assume that hydrocarbon injection is going to work. In order for hydrocarbon injection to work, the category of gas injection must be applicable. In order for gas injection to be applicable both to the oil property data and the reservoir characteristics data must fall within the limits shown in Table 2.

The program starts by trying to verify these subgoals, by asking questions about gravity, viscosity, oil composition, etc. It continues until the final goal is met or until an assumption is rejected at some level. When an assumption is rejected, that branch of the search tree is pruned. The program then moves to the next unpruned branch to the right and picks that EOR process as a goal and continues until a solution is found. In this case, since we want a ranked list of candidate EOR methods, the program searches the tree until all possible solutions are found. When the search is finished, the solutions are printed with a confidence factor for each process. The confidence factors give a ranking to the candidates. They are similar to the rankings in the first program, but not exactly the same.

Figure 16 is an and/or graph for a portion of the search space for the EXSHELL version of the expert assistant. It is called an and/or graph because the branches connected by an arc are "and" branches, that is, all the leaves must be true before the branch is resolved. The unarched branches are "or" branches. They require a single truth for resolution.

An important feature of EXSHELL is that it has an explanation facility. Users may ask "*why*" to any query. EXSHELL will present the rule that it is trying to resolve with that particular query. Users may also ask "*how*" when they want to know how EXSHELL obtained a particular fact. EXSHELL will present the branch of the tree (the list of rules) that led to that fact. When the solution is found, EXSHELL will ask users if they want a trace. EXSHELL can give the entire logic set that led to the solution. One problem with this version of the expert assistant is that it does not capture the numeric score associated with the "goodness" of the EOR criterion for each EOR method, as demonstrated in Figs. 4-14, as well as the CLIPS version does. This will be discussed in the next section.

On the basis of our experience with this particular problem, we feel that it is more easily understood and that the expert assistant is easier to write when it is done in the goal-driven or backward-chaining mode. For this reason, we wanted a backward-chaining method that handled the relative scores as well as the first CLIPS version did. We had the choice of working more with EXSHELL or more with CLIPS. This time we chose to work with CLIPS. We forced CLIPS into the backward-chaining mode and used minimal scores, based on Figs. 4-14, for tree pruning or for eliminating unlikely candidate methods. This version works much like the EXSHELL version, except for the scoring. Figure 17 shows a portion of the search space for this version of the problem in *and/or* graph form. We have also added a simple explanation facility. At the end of the session, the user can ask why a given EOR method was eliminated from consideration. The program will explain which set of EOR criteria values caused the score to drop below the threshold, and therefore, caused that candidate to be eliminated. An example session with this program is described in the appendix.

PROGRAM COMPARISONS AND SUMMARY

The forward-chaining version of the expert assistant was very difficult to write, for this problem, though this is not always the case. Expert system problems are often different, each requiring a different tool or a different approach for the optimal solution. We have used CLIPS and the forward-chaining approach with an expert control system and an advisor to help engineers pick the best equation of state for a given problem (10,11). In the expert systems described in Refs. 10 and 11, we have been able to prune the search tree easily and early. In both of these cases, the categories were more clearly delineated. With the EOR screening problem, even though it is sometimes possible to eliminate all but one EOR category with a few questions, it isn't always possible.

In our first attempt to work the EOR screening problem we tried to write a system that would eliminate all but one category early in the session. We used this approach because it has worked so well for us in the past, that is, we have had problems in which the data have guided us easily through the search tree. In our attempt to try and prune the tree to one category, we had to program in so many contingencies that, quite often, we would not find the best category until we had found the best method.

Another difference with the EOR screening problem is that we are trying to find a ranked list of candidates as opposed to one solution. In

Ref. 11, we produced a small ranked list with our CLIPS program, but all candidates nearly always came from the same category. With the EOR problem, the first and second ranked candidates often come from different categories. With this problem, we don't have to find the "best" path through the search tree, we just have to find all acceptable paths. This reduces some of the advantages that a data-driven approach may have over the goal-driven approach.

Because our first attempt at the forward-chaining approach was so cumbersome, we scrapped it. Our second attempt ended with a program that did a forward-chaining exhaustive search. This program gave a score to every method.

We then wrote our first backward-chaining program with EXSHELL. This was easy because we could actually see how we were progressing with an individual method as the questions were being asked. Writing the backward-chaining approach gave us better insights into the problem. We were then able to go back to the forward-chaining approach, with the new insight, and prune the tree. Our third effort produced an expert system with some intelligence, and it produces answers as good as those produced by the exhaustive search program. With the exhaustive search, CLIPS fired over 300 rules every time with no problems. It actually ran quite fast on a PC-386. This might not be the case with a much bigger expert system that conducts exhaustive searches.

Our EXSHELL version of this program was not without its problems. EXSHELL is written in PROLOG, which deals best with symbolic logic and truth. It deals very well with questions such as, *"Is the formation thin and dipping? Yes or no."* It has more problems with questions like, *"What is the viscosity"?* In our program, the user may need to answer a question such as, *"Is the viscosity less than 15"?* and later on answer the question *"Is the viscosity less than 10"?* This makes the program a little awkward. The real problem, however, is the scoring system. It is easy for EXSHELL to handle probabilities or confidence factors but much more difficult to handle a scoring system such as the one described for the CLIPS versions. For this reason, we lose some of the information shown in Figs. 4-14. On the plus side, EXSHELL has an excellent explanation facility, and it is essentially free. We do not have to program it in.

EXSHELL is easier to program than CLIPS. CLIPS, on the other hand, is more flexible, putting more program control in the user's hands. We were therefore able to force CLIPS to do backward-chaining. We were also able to write a simple explanation facility, but we had to program it ourselves.

We have written three expert assistants, all of which help users perform the first screening step in the selection of an EOR process. Each of the expert assistants is slightly different, but each gives nearly the same results. We have tested them against available data, and they have performed well.

APPENDIX -- SAMPLE SESSION WITH THE EXPERT ASSISTANT

We have chosen the backward-chaining version of the CLIPS expert assistant for the sample session because it is the one we like best and because it is the one we have polished the most.

The example is the first sample problem in this paper, with two added conditions from Table 2. The salinity is 50,000 ppm, and the porosity is 28%. When engineers use this information with Table 2, they will get the same solution that we obtained in our sample session (shown in Fig. 2 and described in the text); the only method that can be used is steam flooding. The expert assistant, however, produces a ranked list of five different candidate processes. They are, in order

	SCORE
(1) Steam flooding	89%
(2) *In situ* combustion	85%
(3) Alkaline flooding	76%
(4) Polymer flooding	73%
(5) Microbial drive	72%

The expert system solves the two problems we had earlier, when we only used Table 1. We get a ranked list of candidates instead of just one candidate or a large unranked list of candidates. It allows methods like *in situ* combustion to be ranked because it uses a relative score to "weigh" problems like *"What does it mean to have a temperature of 110°F when the table says greater than 150°F preferred"?*

The session with the expert assistant is self-explanatory. Some explanation has been built in to this program but the explanation facility is not as sophisticated as the one with EXSHELL.

```
(reset)
CLIPS> (run)

What is the oil saturation (%)? 50

What is the payzone thickness (ft)? 35

Which best describes the reservoir formation?

1 = Mostly sand,
2 = Mostly homogeneous sandstone,
3 = Mostly heterogeneou  sandstone,
4 = Mostly homogeneous carbonate,
5 = Mostly heterogeneous carbonate
6 = Nonspecific or Unknown       2

What is the formation porosity (%)? 28

What is the formation salinity (ppm)? 50000

What is the formation temperature (°F)? 110

What is the oil gravity (API)? 18

Which best describes the oil composition
Note:  The choices are in increasing order of importance.

1 = Asphaltic components and Organic acids (0.4 mg/g oil),
2 = Asphaltic components & any weight of oil,
3 = Organic acids (0.4 mg/g oil) & any weight of oil,
4 = A high % of low-weight components (C1-C7),
5 = A high % of medium-weight components (C2-C7),
6 = A high % of high-weight components (C5-C12), or
7 - No predominant major components mentioned above. 5

What is the formation permeability (md)? 1000

What is the oil viscosity (cp)? 500

What is the well depth (feet)? 2000

The method, Microbial was found to be a
suitable EOR process with a certainty of       72%.
```

The method, In-Situ-Combustion was found to be a suitable EOR process with a certainty of - 85%.

The method, Steam-Flooding was found to be a suitable EOR process with a certainty of - 89%.

The method, Polymer-Flooding was found to be a suitable EOR process with a certainty of - 73%.

The method, Alkaline-Flooding was found to be a suitable EOR process with a certainty of - 76%.

Would you like to see an explanation of why the methods not show in the final results were eliminated (*'yes'* or *'no'*)?

The category, Gas-Injection did not score well enough (>25) to continue investigating any methods in this category. The reason for this is based on the ratings assessed for the parameters;

Permeability Grade	=	10
Well Depth Grade	=	0
Viscosity Grade	=	11

Would you like to continue (*'yes'* or *'no'*)? *yes*

The method, Surfactant-Polymer's oil characteristics score was not good enough (>25) to continue investigating this method. The reason for this based on the ratings assessed for the parameters;

Temperature Grade	=	10
Oil Grade	=	0
Oil Composition Grade	=	11

The method, Carbon-Dioxide's oil characteristics score was not good enough (>25) to continue investigating this method. The reason for this is based on the ratings assessed for the parameters;

Temperature Grade = 12
Oil Gravity Grade = 3
Oil Composition Grade = 6

The method, Nitrogen-Flue-Gas's oil characteristics score was not good enough (>25) to continue investigating this method. The reason for this is based on the ratings assessed for the parameters;

Temperature Grade = 10
Oil Gravity Grade = 2
Oil Composition Grade = 10

301 rules fired
run time is 75.1640625 seconds

REFERENCES

1. J. J. G. Stosur, "The Potential of Enhanced Oil Recovery," *International Journal of Energy Research*, Vol. 10, 357-370 (1986).

2. J. C. Giarratano, *CLIPS User's Guide*, Version 4.3 of Clips Artificial Intelligence Section, Lyndon B. Johnson Space Center (June 1989).

3. G. F. Luger and W. A. Stubblefield, *Artificial Intelligence and the Design of Expert Systems* (the Benjamen/Cummings Publishing Company, Inc., Redwood City, California, 1989).

4. J. J. Taber and F. D. Martin, "Technical Screening Guides for Enhanced Recovery of Oil," paper presented at the 58th Annual Society of Petroleum Engineers Technical Conference, San Francisco, California, October 5-8, 1983 (SPE 12069).

5. G. O. Goodlett, H. M. Honarpour, H. B. Carroll, and P. S. Sarathi, "Lab Evaluation Requires Appropriate Techniques--Screening for EOR-1," *Oil and Gas Journal* (June 23, 1986), pp. 47-54.

6. G. O. Goodlet, H. M. Honarpour, H. B. Carroll, P. Sarathi, T. H. Chung, and D. K. Olsen, "Screening and Laboratory Flow Studies for Evaluating EOR

Methods," Topical report DE87001203, Bartlesville Project Office, USDOE (Bartlesville Oklahoma, November 1986).

7. E. C. Donaldson, G. V. Chilingarian, and T. F. Yen, Eds., *Enhanced Oil Recovery, I, Fundamentals and Analysis* (Elsevier, New York, 1985).

8. F. H. Poettmann, Ed., *Improved Oil Recovery, The Interstate Oil Compact Commission* (Oklahoma City, Oklahoma, 1983).

9. "Enhanced Recovery Methods are Worldwide" (Petroleum Publishing Company, 1976). (Compiled from issues of The Oil and Gas Journal.)

10. W. J. Parkinson, P. D. Shalek, E. J. Peterson, and G. F. Luger, "Designing and Expert System for the Production of Silicon Carbide Whiskers," presented at the TMS Annual Meeting, Symposium--Expert System Applications in Materials Processing & Manufacturing (February 19-22, 1990, Anaheim, California).

11. W. J. Parkinson, G. F. Luger, and R. E. Bretz, "Using PC-Based Shells to Write an Expert Assistant for Use with the ASPEN Computer Code," Paper presented at the AIChE Annual Meeting, Session on Applications of Artificial Intelligence in Chemical Engineering (April 2-6, 1989, Houston, Texas).

TABLE 1

SUMMARY FOR SCREENING CRITERIA FOR ENHANCED RECOVERY METHODS[c]

	Oil Properties			Reservoir Characteristics					
	Gravity °API	Viscosity (cp)	Composition	Oil Saturation	Formation type	Net Thickness (ft)	Average Permeability (md)	Depth (ft.)	Temperature (°F)
Gas Injection Methods									
Hydrocarbon	>35	<10	High % of C_2 - C_7	>30% PV	Sandstone or Carbonate	Thin unless dipping	NC	>2000 (LPG) to <5000 HP gas	NC
Nitrogen & Flue Gas	>24 >35 for N	<10	High % of C_1 - C_7	>30% PV	Sandstone or Carbonate	Thin unless dipping	NC	>4500	NC
Carbon Dioxide	>26	<15	High % of C_5 - C_{12}	>30% PV	Sandstone or Carbonate	Thin unless dipping	NC	>2000	NC
Chemical Flooding									
Surfactant/Polymer	>25	<30	Light intermediates desired	>30% PV	Sandstone preferred	>10	>20	<8000	<175
Polymer	>25	<150	NC	>10% PV Mobile oil	Sandstone preferred Carbonate possible	NC	>10 (normally)	<9000	<200
Alkaline	13-35	<200	Some organic Acids	Above waterflood residual	Sandstone preferred	NC	>20	<9000	<200
Thermal									
Combustion	<40 (10-25 normally)	<1000	Some asphaltic components	>40-50% PV	Sand or Sandstone with high porosity	>10	>100[a]	>150 preferred	>150 preferred
Steamflooding	<25	>20	NC	>40-50% PV	Sand or Sandstone with high porosity	>20	>200[b]	300-5000	NC

NC = not critical

a Transmissibility >20 md ft/cp

b Transmissibility >100 md ft/cp

c From reference 4.

TABLE 2

SUMMARY OF SCREENING CRITERIA FOR ENHANCED RECOVERY METHODS [e]

	Oil Properties				Reservoir Characteristics						
	Gravity °API	Viscosity (cp)	Composition	Salinity (ppm)	Oil saturation	Formation type	Net Thickness (ft)	Average permeability (md)	Depth (ft.)	Temperature (°F)	Porosity %
Gas injection methods											
Hydrocarbon	>35	<10	High % of C_2-C_7	NC	>30% PV	Sandstone or Carbonate	Thin unless dipping	NC	>2000 (LPG) to >5000 (HP gas)	NC	NC
Nitrogen & flue gas	>24 >35 for N_2	<10	High % of C_1-C_7	NC	>30% PV	Sandstone of Carbonate	Thin unless dipping	NC	>4500	NC	NC
Carbon dioxide	>26	<15	High % of C_5-C_{12}	NC	>30% PV	Sandstone or Carbonate	Thin unless dipping	NC	>2000	NC	NC
Chemical Flooding											
Surfactant polymer	>25	<30	Light inter-mediates desired	<140,000	>30% PV	Sandstone preferred	>10	>20	<8000	<175	≥20
Polymer	>25	<150	NC	<100,000	>10% PV Mobile oil	Sandstone preferred Carbonate possible	NC	>10 (normally)	<9000	<200	≥20
Alkaline	13-35	<200	Some organic Acids	<100,000	Above water-flood residual	Sandstone preferred	NC	>20	<9000	<200	≥20
Thermal											
Combustion	>40 (10-25 normally)	<1000	Some asphaltic components	NC	>40-50% PV	Sand or Sandstone with high porosity	>10	>100 [a]	>500	>150 preferred	≥20 [c]
Steamflooding	<25	>20	NC	NC	>40-50% PV	Sand or Sandstone with high porosity	>20	>200 [b]	300-5,000	NC	≥20 [d]
Microbial											
Microbial drive	>15	-	Absence of toxic conc. of metals. No biocides present	<100,000	NC	Sandstone or Carbonate	NC	>150	<8000	<140	---

NC = Not Critical

a Transmissibility >20 md ft/cp

b Transmissibility > 100 md ft/cp

c Ignore if saturation times porosity > 0.08

d Ignore if saturation times porosity > 0.1

e Modified from Refs. 4 and 6.

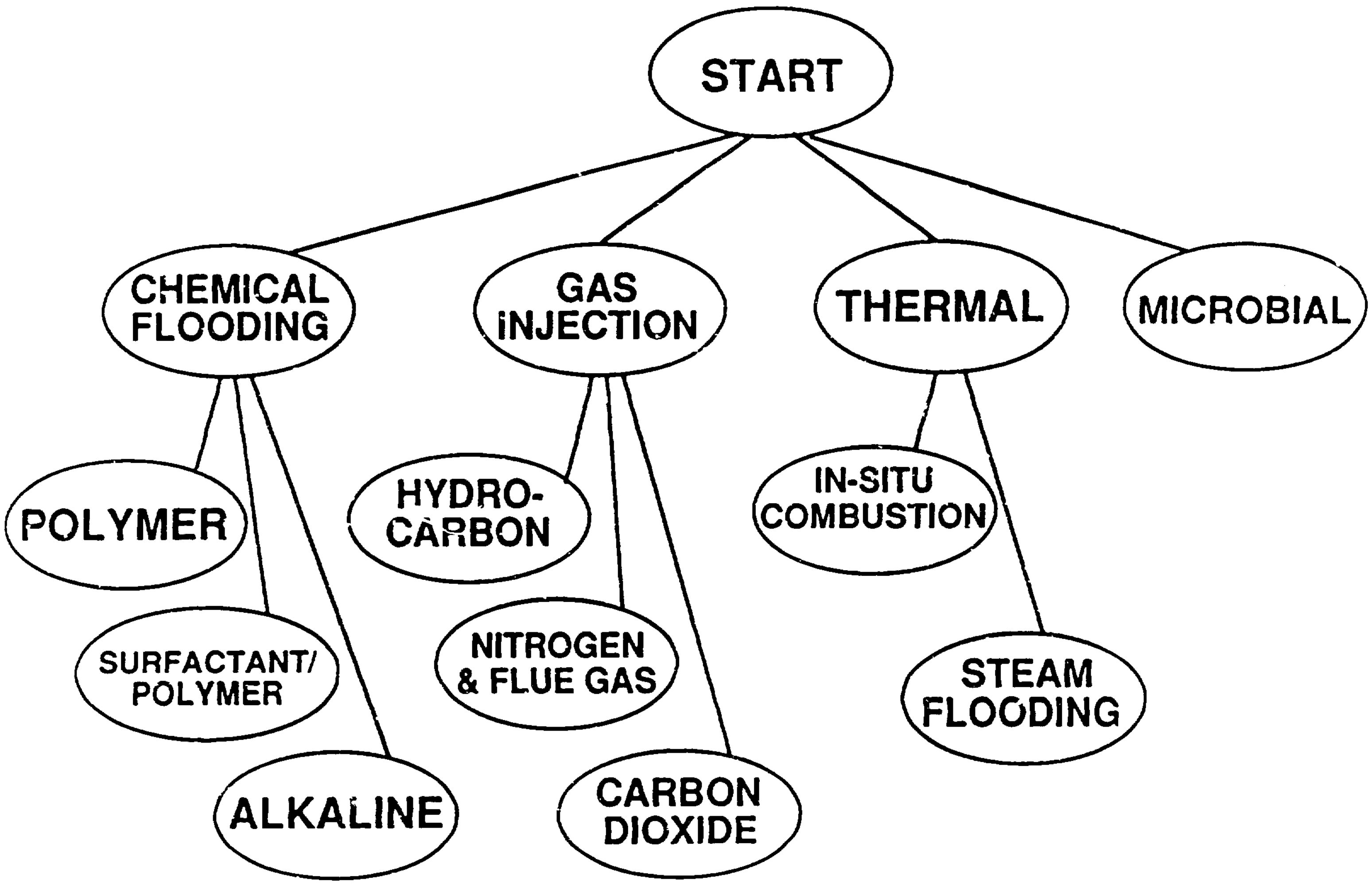


Figure 1. Search tree for the expert assistant.

SOLUTION TO EXAMPLE PROBLEM 1

Gas Injection Methods	Gravity	Viscosity	Composition	Oil Saturation	Formation Type	Net Thickness	Average Permeability	Depth	Temperature
Hydrocarbon	no	→	→	→	→	→	→	→	→
Nitrogen & Flue Gas	no	→	→	→	→	→	→	→	→
Carbon Dioxide	no	→	→	→	→	→	→	→	→
Chemical Flooding									
Surfactant/Polymer	no	→	→	→	→	→	→	→	→
Polymer	no	→	→	→	→	→	→	→	→
Alkaline	yes	no	→	→	→	→	→	→	→
Thermal									
Combustion	yes	yes	yes	yes	yes	yes	yes	yes	no
Steam Flooding	yes	yes	NC	yes	yes	yes	yes	yes	NC

NC = not critical

Figure 2

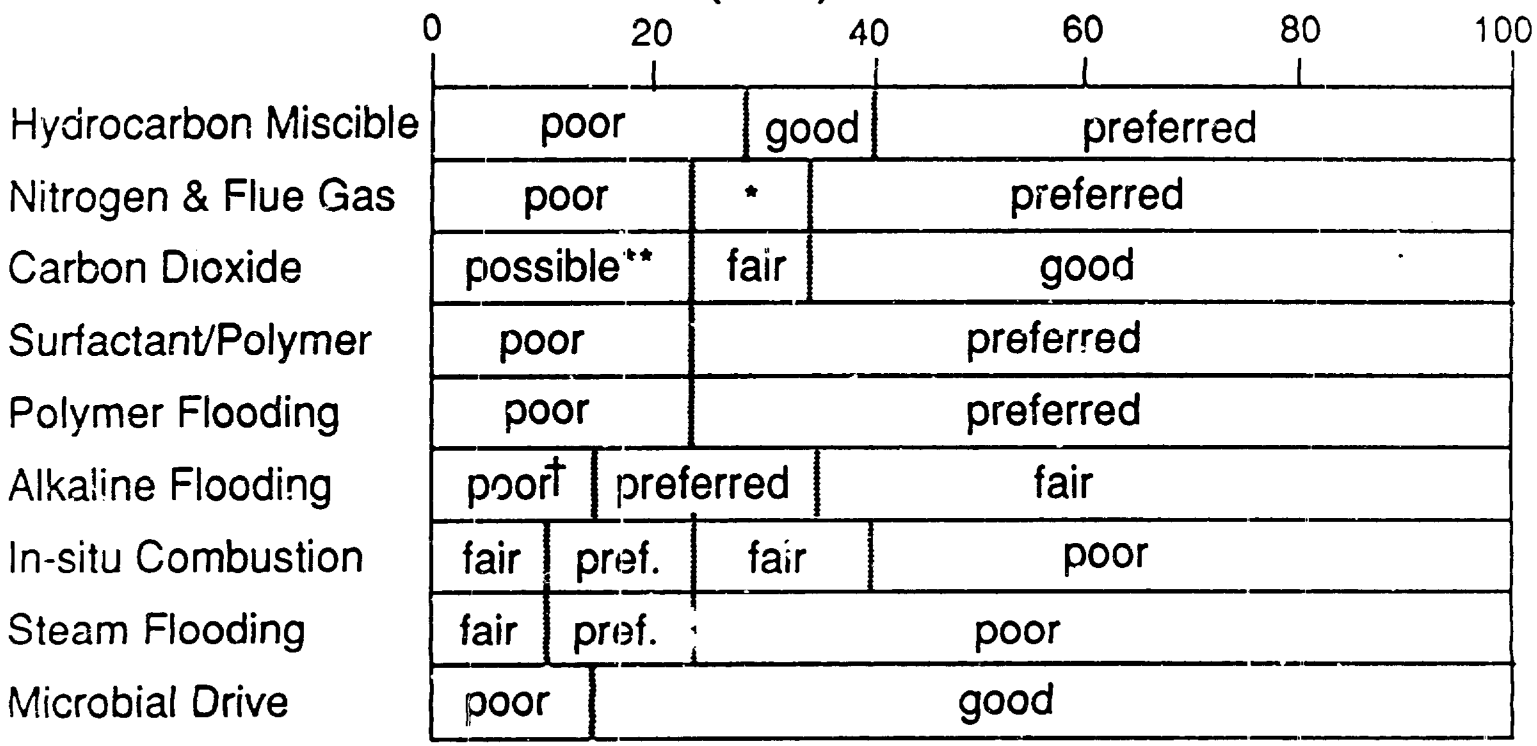
SOLUTION TO EXAMPLE PROBLEM 2

Gas Injection Methods	Gravity	Viscosity	Composition	Oil Saturation	Formation Type	Net Thickness	Average Permeability	Depth	Temperature
Hydrocarbon	yes	yes	ok	yes	yes	ok	NC	yes	NC
Nitrogen & Flue Gas	yes	yes	ok	yes	yes	ok	NC	yes	NC
Carbon Dioxide	yes	yes	ok	yes	yes	ok	NC	yes	NC
Chemical Flooding									
Surfactant/Polymer	yes	yes	ok	yes	yes	yes	yes	yes	yes
Polymer	yes	yes	NC	yes	yes	NC	yes	yes	yes
Alkaline	yes	yes	ok	yes	yes	NC	yes	yes	yes
Thermal									
Combustion	yes	yes	ok	yes	yes	yes	yes	yes	NC
Steam Flooding	no	→	→	→	→	→	→	→	→

NC = not critical

Figure 3

OIL GRAVITY SCREENING DATA
(°API)



* Minimum preferred, 24 for flue gas and 35 for nitrogen.
** Possible imMiscible gas displacement.
† No organic acids are present at this gravity.

Figure 4

OIL VISCOSITY SCREENING DATA
(CP)

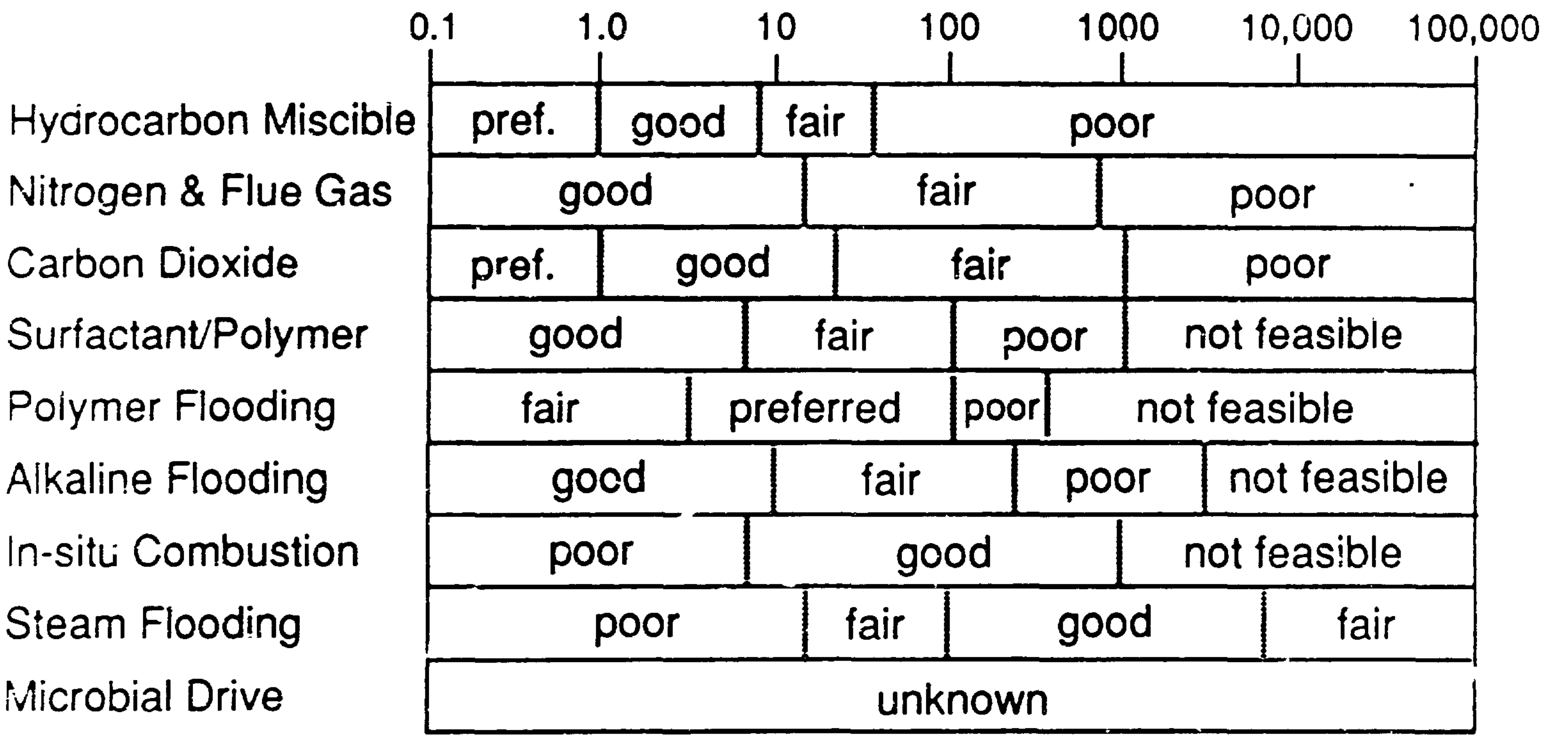


Figure 5

OIL COMPOSITION SCREENING DATA

	High % C_2 - C_7	High % C_1 - C_7	High % C_5 - C_{12}	Organic Acids	Asphaltic Components
Hydrocarbon Miscible	preferred	good	fair	NC	NC
Nitrogen & Flue Gas	good	preferred	fair	NC	NC
Carbon Dioxide	fair	fair	preferred	NC	NC
Surfactant/Polymer	fair	fair	preferred	NC	NC
Polymer Flooding	NC	NC	NC	NC	NC
Alkaline Flooding	NC	NC	NC	preferred	NC
In-situ Combustion	NC	NC	NC	NC	preferred
Steam Flooding	NC	NC	NC	NC	NC
Microbial Drive	NC	NC	NC	NC	NC

NC = not critical

Figure 6

FORMATION SALINITY SCREENING DATA
(ppm)

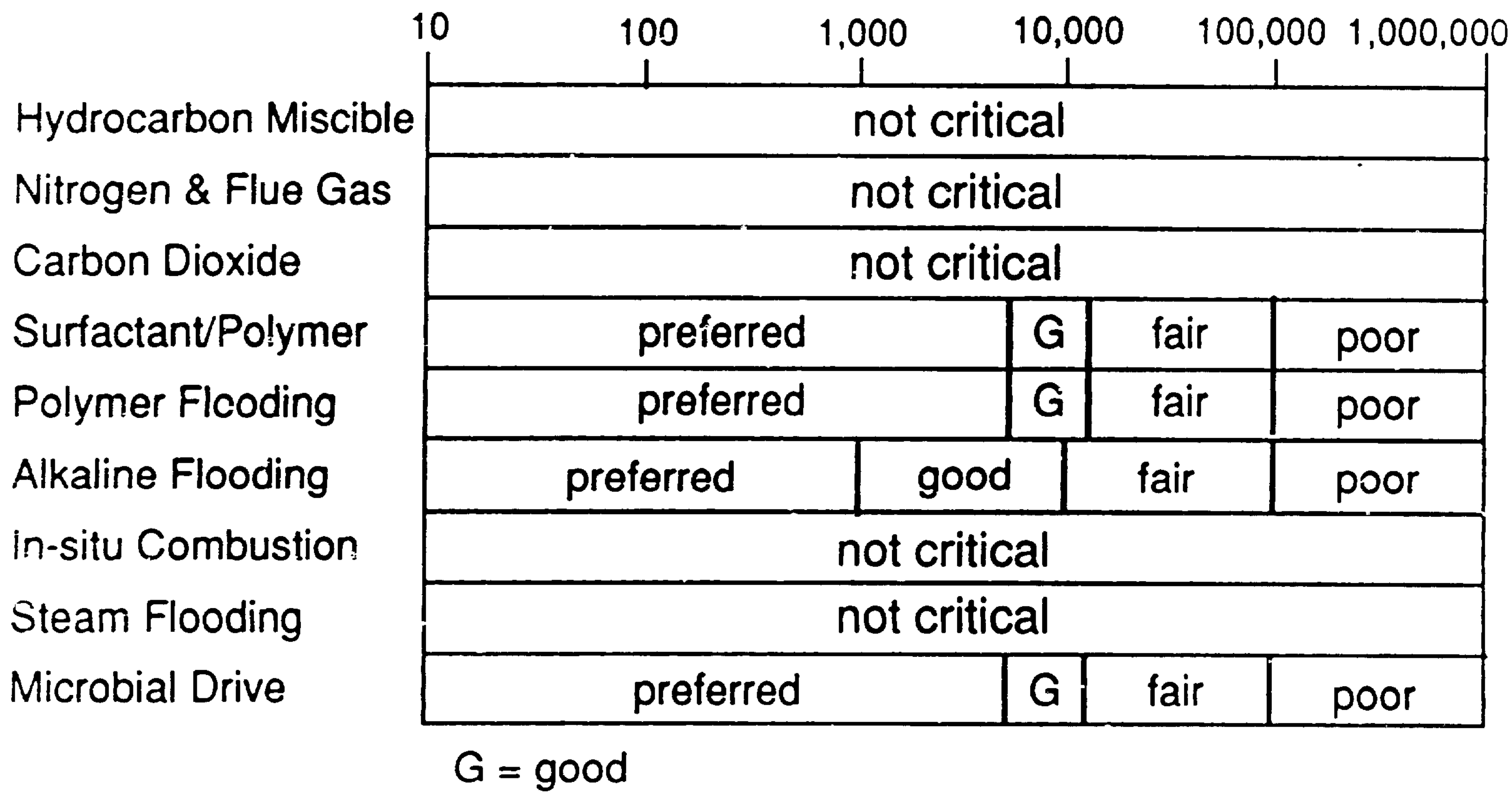
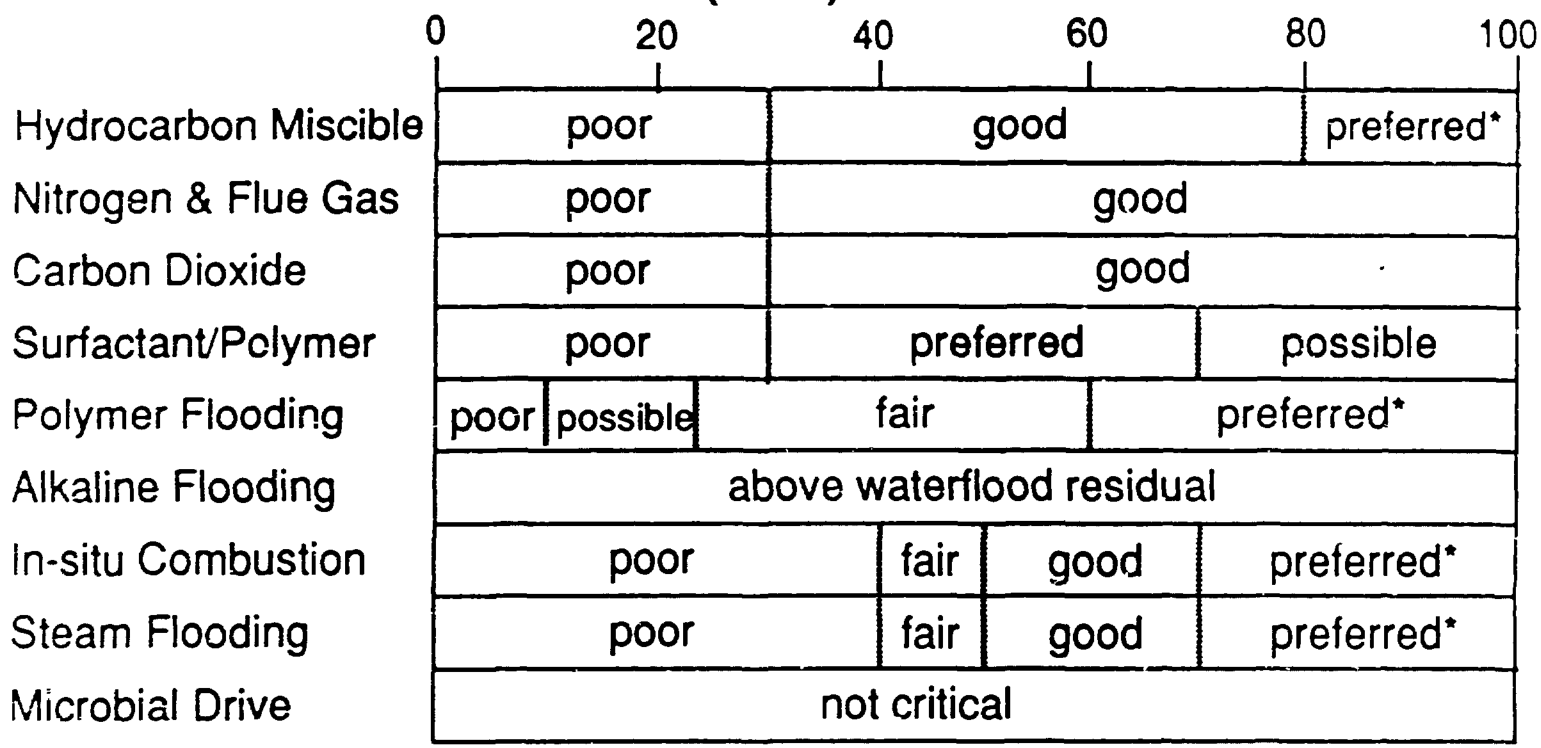


Figure 7

OIL SATURATION SCREENING DATA
(%PV)



* Preferred status is based on the starting residual oil saturations of successfully producing wells as documented by Ref. 9.

Figure 8

FORMATION TYPE SCREENING DATA

	Sand	Homogeneous Sandstone	Heterogeneous Sandstone	Homogeneous Carbonate	Heterogeneous Carbonate
Hydrocarbon Miscible	good	good	poor	good	poor
Nitrogen & Flue Gas	good	good	poor	good	poor
Carbon Dioxide	good	good	poor	good	poor
Surfactant/Polymer	preferred	preferred	poor	good	poor
Polymer Flooding	preferred	preferred	good	fair	poor
Alkaline Flooding	poor	preferred	fair	not feasible	not feasible
In-situ Combustion	good	good	good	good	fair
Steam Flooding	good	good	fair	good	fair
Microbial Drive	good	good	poor	good	poor

Figure 9

NET THICKNESS OF SCREENING DATA
(FEET)

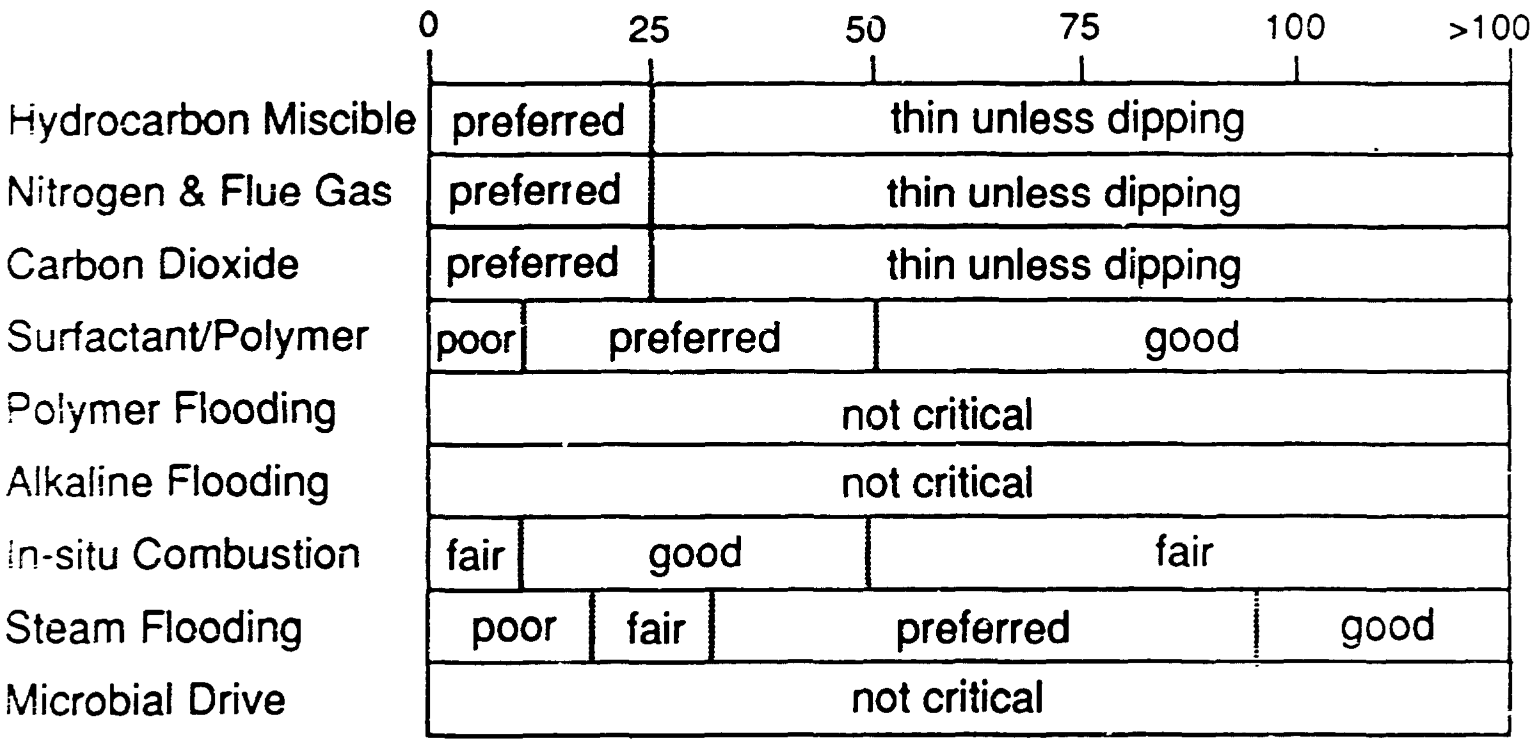


Figure 10

PERMEABILITY SCREENING DATA
(md)

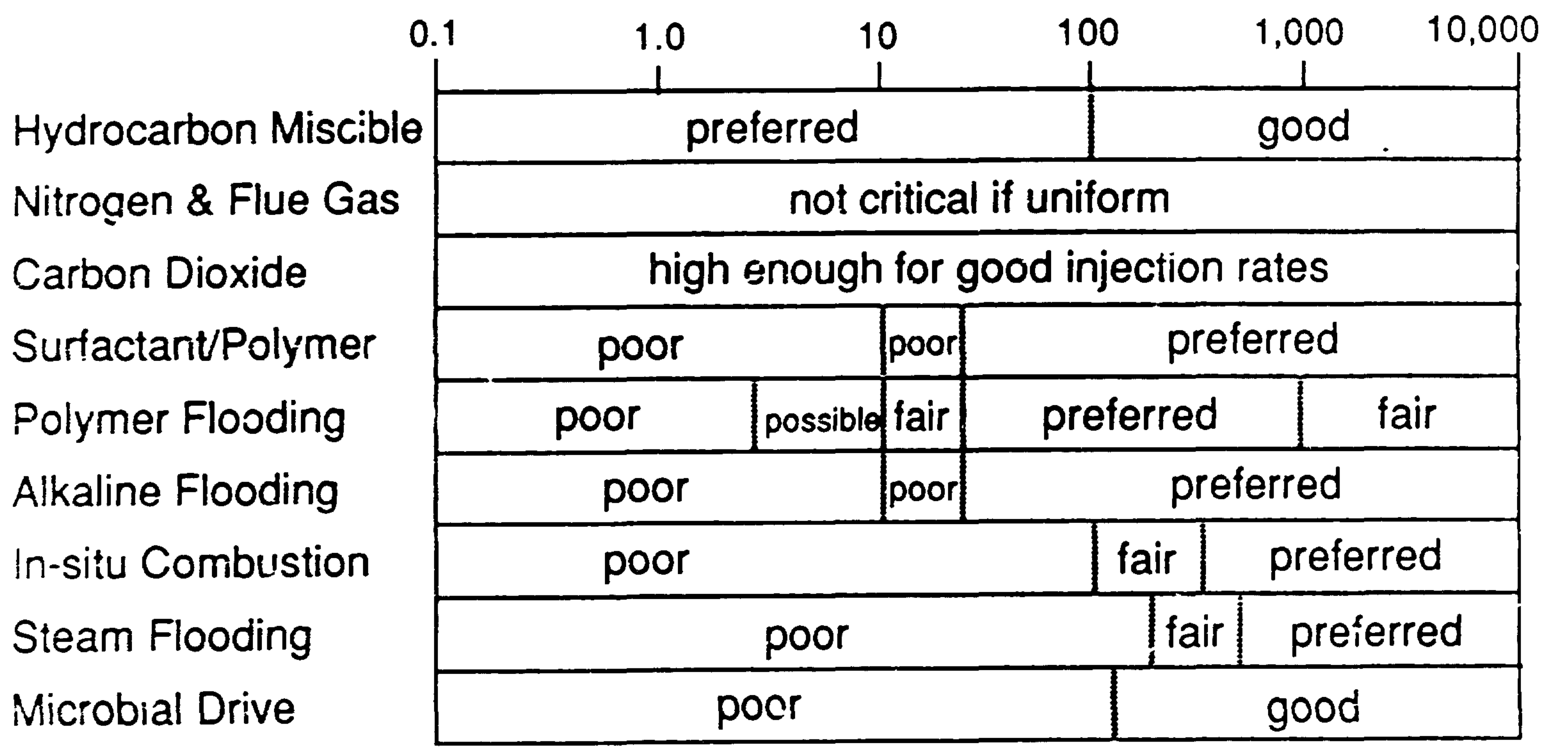
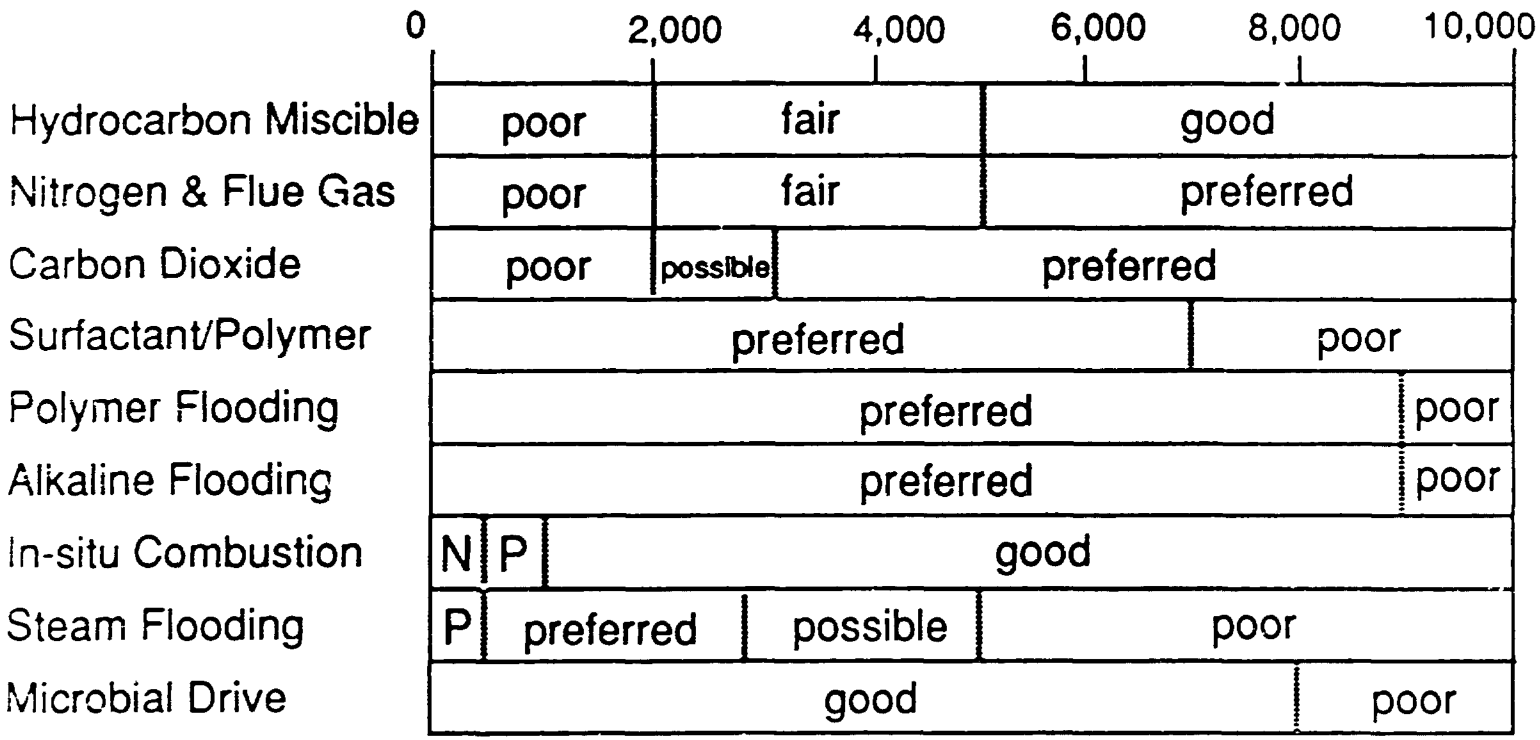


Figure 11

WELL DEPTH SCREENING DATA
(FEET)



P = possible N = not feasible

Figure 12

FORMATION TEMPERATURE SCREENING DATA
(°F)

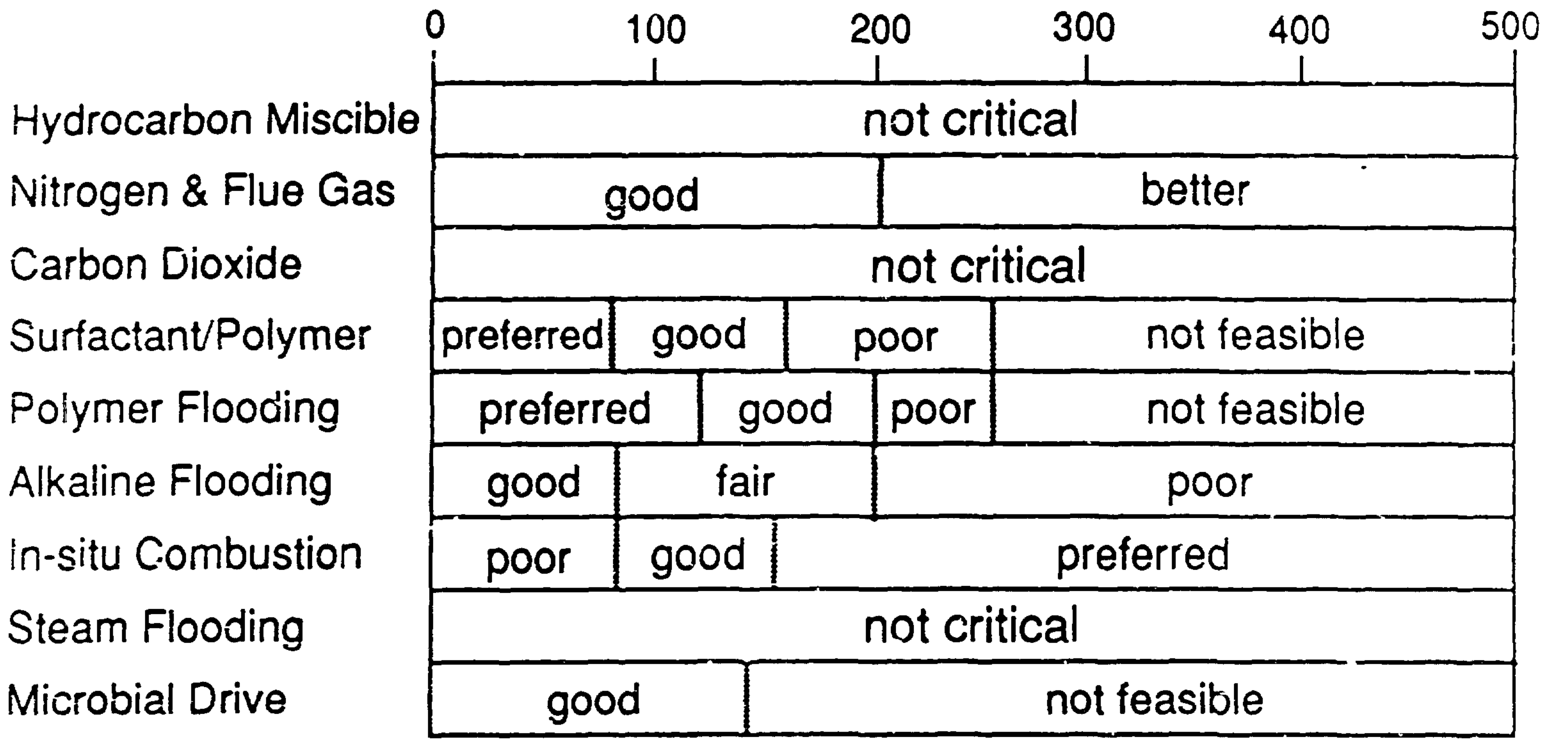


Figure 13

FORMATION POROSITY SCREENING DATA
(%)

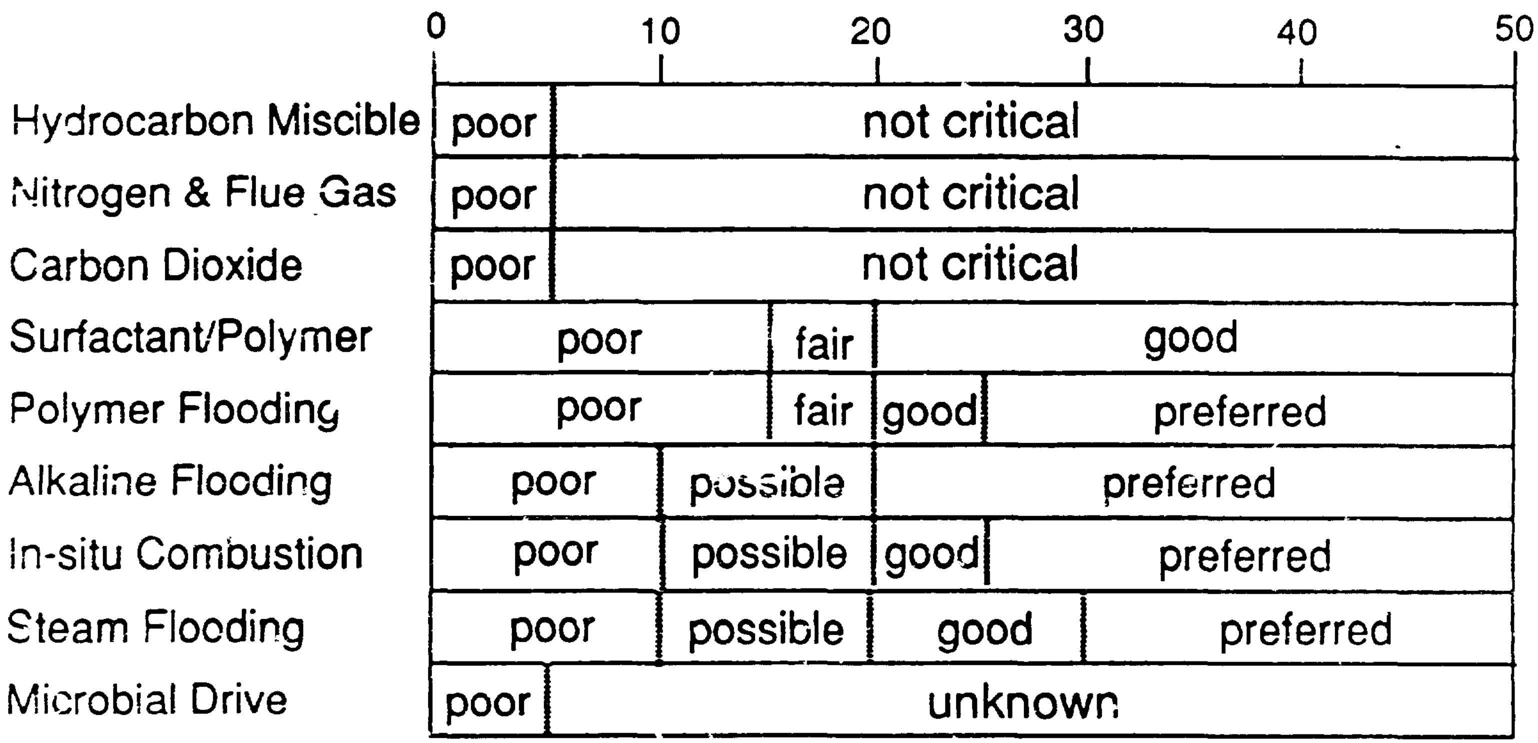


Figure 14

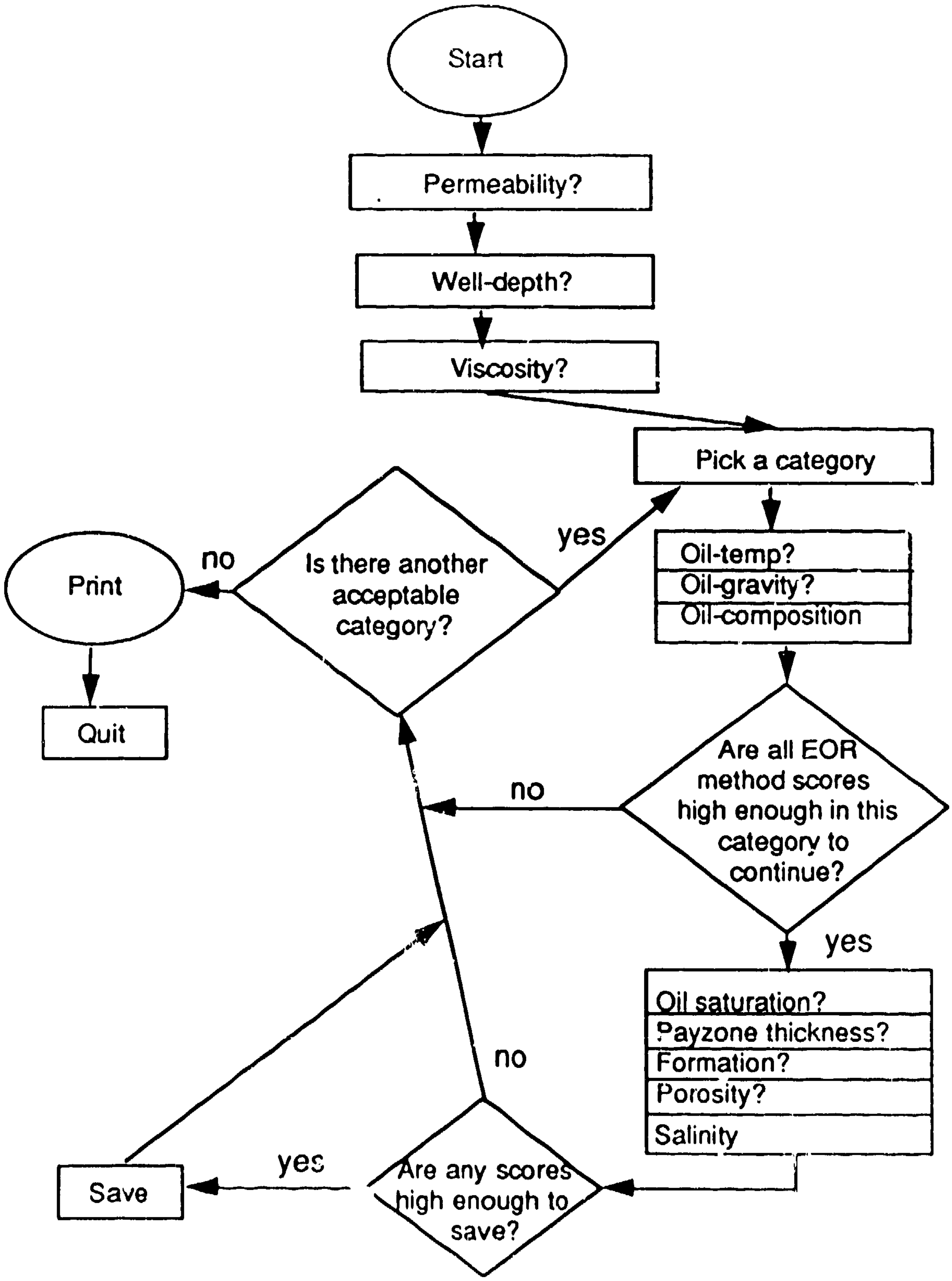


Figure 15. F'ow diagram for the CLIPS forward-chaining version of the problem.

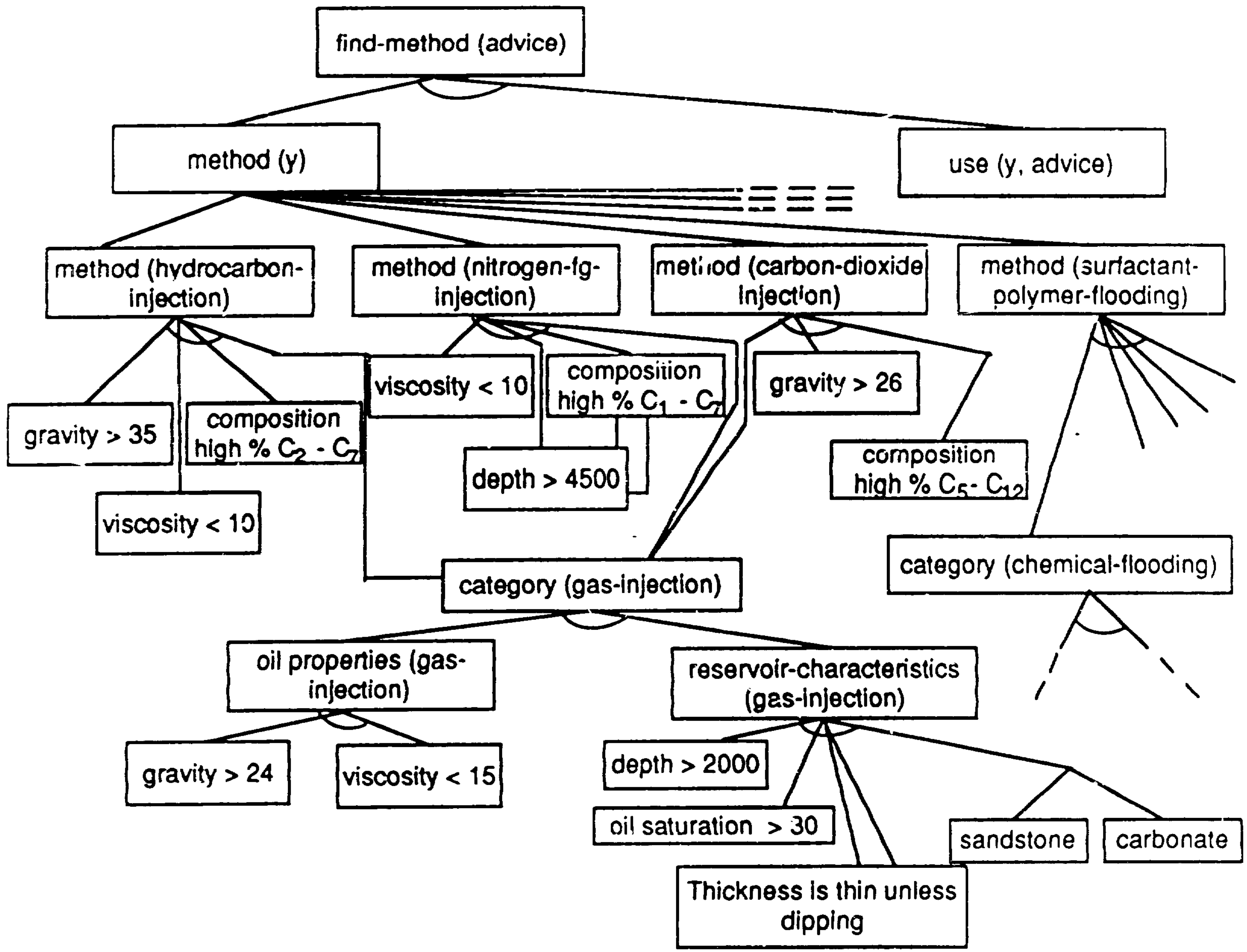


Figure 16. And/or graph for a portion of the search space for the EXSHELL version of the EOR screening expert assistant.

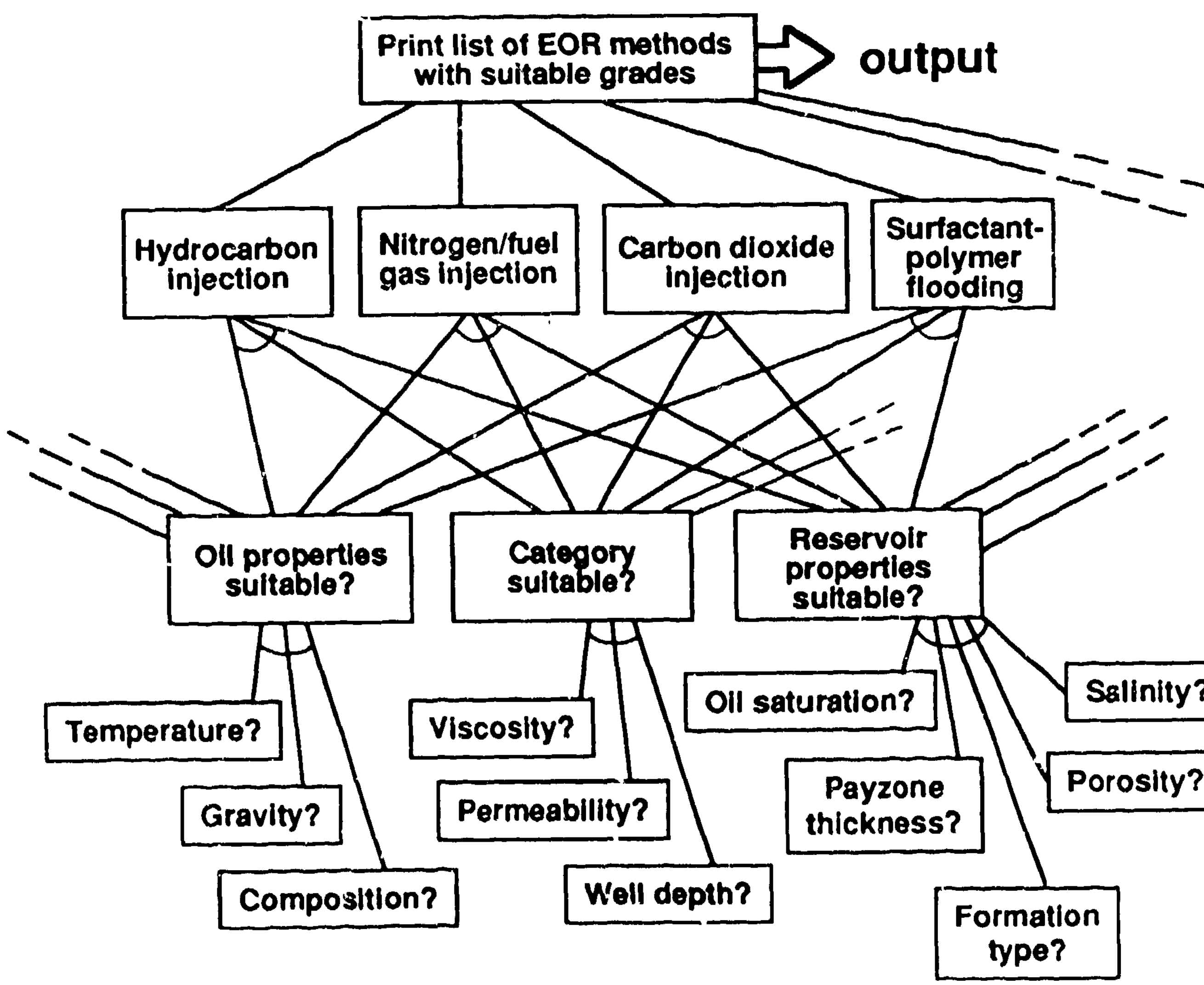


Figure 17. And/or graph for a portion of the search space for the CLIPS backward-chaining version of the problem.