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Screening Methods Help Operators Identify Viable EOR Opportunities

By Eduardo Manrique and John D. Wright

GOLDEN, CO.–Most of the world's oil production comes from mature fields, and increasing output from these aging resources is a major concern for oil companies, national resource holders and regulators alike. From the mid-1980s to 2003, low oil prices not only reduced the number of enhanced oil recovery field projects, but also the research and development of new EOR methods. Additionally, new discoveries have been declining steadily over the past few decades. Boosting oil recovery from mature fields in known basins now undergoing primary and secondary production will be critical to meeting growing market demand. Therefore, it becomes clear that aging resources will require proven and innovative EOR technologies to increase their economic value, replace or upgrade reserves, and extend their productive lives.

With oil prices increasing to the $40-$75 range over the past few years, EOR has once again become attractive. Operators are developing or requiring fast and reliable assessments that identify the technical and economic feasibility of implementing EOR, or that justify the acquisition of a particular property based on its EOR potential. However, a fair question operators may have is: What approach is most suitable for evaluating technical and economic EOR potential under conditions of limited information and time constraints?

Generally, oil and gas companies from majors to independents may operate a large number of reservoirs with limited data. In other cases, reservoirs lack enough financial performance to justify the gathering of those data. The latter represents a common barrier to identifying appropriate investment opportunities during oil property evaluation in one or a portfolio of reservoirs. Additionally, complexity, CAPEX, OPEX and the number of options available for EOR make the decision process more difficult.

Several approaches have been used to evaluate the applicability of EOR processes. However, the best way to support the decision-making processes for EOR projects and oil property acquisitions is a systematic approach for evaluating and ranking technical and economic EOR opportunities within a risk management framework based on previous field experiences. Basically, this methodology integrates three major steps into the analysis:

- EOR screening criteria based on geological and reservoir properties from previous oil field experiences;
- Numerical or analytical simulation coupled with decision-risk models; and
- Economic evaluation and ranking of EOR opportunities.

It is important to mention that this methodology can be performed with any kind of commercial, public (e.g., U.S. Department of Energy analytical models), or proprietary software. Additionally, previous field experience and EOR screening criteria have been widely reported in industry literature. Consequently, this approach uses a database that consolidates some 1,600 international EOR projects to develop an advanced screening method based on previous EOR field experience.

EOR Screening

One of the major challenges of EOR screening is to manage and relate a large portfolio of reservoirs produced under dissimilar exploitation strategies and conditions with different EOR methods under time constraints and with limited information. This is especially true in mature fields requiring fast decision-making processes to extend reservoir production life through EOR projects. On the other hand, EOR screening represents a key step to reducing the number of options for further detailed evaluations. The systematic methodology considers both geologic and reservoir screening criteria.

EOR screening criteria have been widely used to evaluate a number of reservoirs before any detailed evaluation is performed. Geologic screening criteria ("predictive geology") have been used to a lesser extent, although the impact of large-scale geological heterogeneities on the recovery of oil has been well documented. Generally, a reservoir or portfolio of reservoirs under evaluation is compared with the main geologic properties of previous EOR field experience. Examples of the main criteria considered include geologic age, basin, depositional environment, dip angle, diagenesis, trap type, structure, lithology, and reservoir heterogeneity.

Figure 1 shows an example of 200 steamflood projects in heavy oil sandstone reservoirs with different depositional environments, also known as the Tyler and Finley heterogeneity matrix (1991). Of these 200 steamflooding projects, 185 were reported by the operators as successful (blue parentheses) and 15 failed (red brackets). Although the location of EOR projects in this type of matrix is somewhat subjective because of the lack of geologic information or differences in the geologic interpretation, this type of analysis provides guidance for the decision-

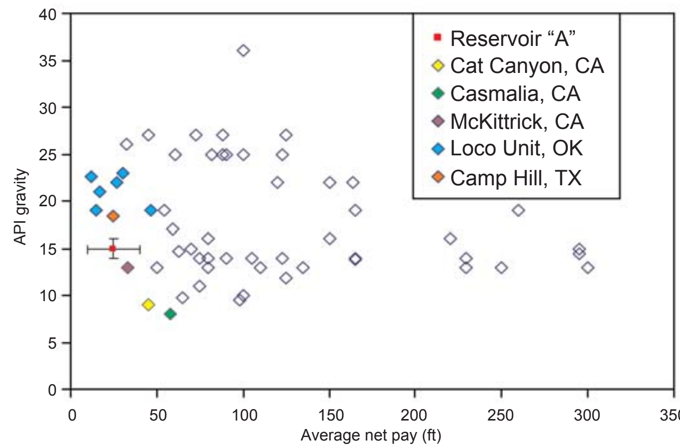
FIGURE 1

Steamflood Projects as a Function of the Depositional Environment

Vertical Heterogeneity	Lateral Heterogeneity: Low	Lateral Heterogeneity: Moderate	Lateral Heterogeneity: High
Low	Wave-dominated delta Barrier core Barrier shore face Sand-rich strand plain (9)	Delta-front mouth bars Proximal delta front (accretionary) Tidal Deposits Mud-rich strand plain (7) / [3]	Meander belts* Fluvially dominated delta* Back Barrier* (0)
Moderate	Eolian Wave modified delta (distal) (9) / [2]	Shelf barriers Alluvial Fans Fan Delta Lacustrine delta Distal delta front (83) / [9]	Braided stream Tide-dominated delta (52)
High	Basin-flooding turbidites (19)	Coarse-grained meander belt Braid delta (2)	Back barrier** Fluvially dominated delta** Fine-grained meander belt** Submarine fans** (4) / [1]

FIGURE 2

API Gravity versus Average Net Pay of International Steamfloods



making process associated with EOR projects.

Additionally, with the dimensions of sand bodies or genetic units (length, thickness, and width), lateral and vertical heterogeneities can be estimated through simple equations creating a Tyler and Finley type of heterogeneity matrix. Adapting this approach has been particularly useful in evaluating steam-assisted gravity drainage (SAGD) projects in Canada by estimating the technical feasibility of horizontal well length, vertical separation of horizontal wells, and well-pair spacing based on sand body architectures.

EOR Reservoir Screening

Screening models have been widely used to identify EOR applicability in a particular field before any detailed evaluation is started. The EOR reservoir screening analysis is divided into two stages: conventional and advanced EOR screening criteria. Both screening criteria are based on a set of reservoir parameters (e.g., depth, temperature, pressures, permeability, oil saturation, and viscosity) generally obtained from either field experience (success and failure) or from an understanding of the characteristics and physics or chemistry of each EOR process.

During conventional screening, a reservoir or portfolio of reservoirs are compared with the 1,600 international EOR field projects in the database using 2-D plot representations and a fast proximity criterion with two average field or fluid variables. Figure 2 shows an example of a 2-D steamflood plot identifying analog fields and a shallow heavy oil reservoir under evaluation (Reservoir "A"). The identification of field experiences with similar reservoir properties can be used as a preliminary guide to reduce the potential risks and uncertainties associated with a proposed EOR project. However, the identification of successful field experiences cannot always be seen on pair-by-pair comparisons with the database. Therefore, advanced EOR screening methods are recommended.

Advanced EOR screening criteria is performed using a machine-learning approach. This approach is based first on space reduction techniques to simplify the representation of international EOR experiences in a collated database of reservoirs and projected as 2-D cluster maps, also called "reservoir typology." The method is based on a reduced set of reservoir variables generating 2-D representations ("expert maps") with clusters of reservoirs types having common kinds of EOR projects considering six reservoir variables: API gravity, temperature, oil viscosity, permeability, porosity, and reservoir pressure at the beginning of the oil recovery project.

In Figure 3, six clusters or reservoir typologies are shown (for simplicity, the frequency of EOR usage applied to each cluster is not included). Cluster 6 is dominated by high-pressure, high-temperature (HP/HT) reservoirs. In contrast, Cluster

FIGURE 3

EOR Project Projections using Expert Map

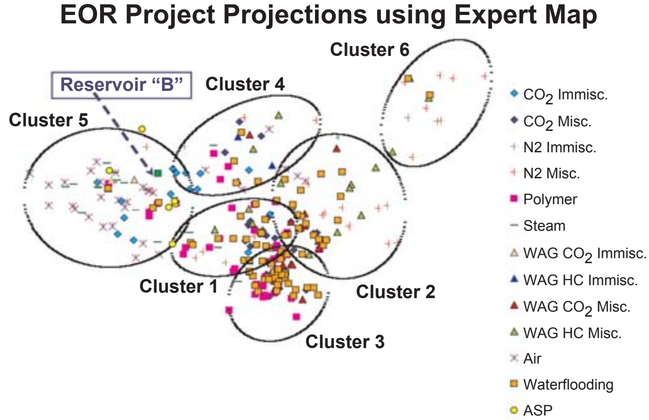
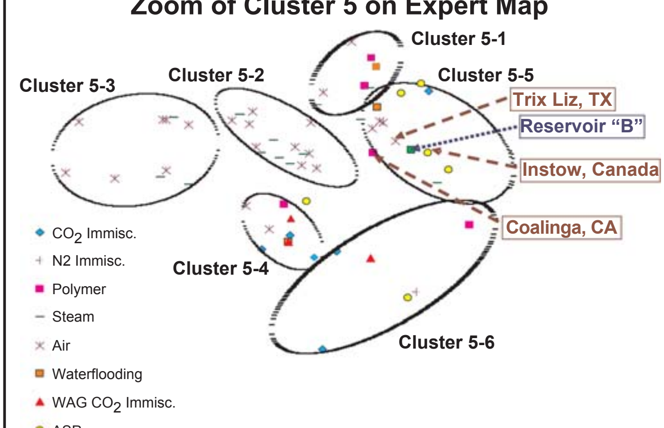


FIGURE 4

Zoom of Cluster 5 on Expert Map



5 is dominated by depleted and heavy oil reservoirs, where thermal methods and chemical methods represent nearly 80 percent of the EOR processes applied in this reservoir typology.

Figure 3 also shows the location of a medium-gravity crude oil (24 degree API) reservoir where an alkaline-surfactant-polymer (ASP) flood was recommended (Reservoir "B," green square). To more precisely determine analog reservoirs and adequate EOR approximations to Reservoir B, a reprocessing of Cluster 5 data is presented in Figure 4. This analysis shows that Trix Liz in Texas (air injection), Coalinga in California (polymer flood), and Instow in Canada (ASP) are closer analogs to the reservoir under evaluation.

In addition, it can be seen that Reservoir B belongs to a reservoir typology (Cluster 5-5) with a representative number of chemical floods, which reduces some risk and uncertainties associated with the applicability of this recovery method. Reviewing the literature and documents publicly available related to the geological features and local operating conditions of those ASP field examples usually contributes to making the decision on pilot project design and operational experiences.

This screening procedure has demonstrated its effectiveness for identifying EOR opportunities that reduce the number of EOR options that need to be analyzed in more detail in the simulation and economic evaluation phases. Finally, considering the availability of potential injectants (e.g., CO_2 sources or natural gas for steam generation), environmental impacts and political issues at early stages of the screening are strongly recommended.

EOR Project Simulation

Once the screening step is completed, the next step is predicting the oil production of selected EOR processes using either analytical or numerical simulation. In this phase, variables such as oil production rates, cumulative oil production, and final recoveries can be used to rank the EOR processes identified in the screening phase.

Generally, numerical reservoir simulation represents the first choice of most operators for evaluating reservoir performance under different exploitation schemes, including EOR methods. If enough quality laboratory and field data or history-matched reservoir models are available to simulate a specific EOR process, numerical simulation represents the most reasonable way to predict the reservoir performance of an EOR method. In these cases, 2-D (cross-section) or 3-D (e.g., well pattern or single SAGD well pair) models can be used to rank EOR methods based on performance. It is highly probable that different 2- or 3-D models will be required to consider the impact of potential lateral and vertical reservoir heterogeneities on oil recovery. Again, this will depend on the information available and the details required in the analysis.

In cases where reservoir simulation studies are not justified from the available data or when unrealistic reservoir description needs to be performed to achieve a history match of a particular reservoir, a simplified modeling tool is recommended. In addition, EOR methods such as chemical floods and air injection require detailed laboratory data to be able to properly simulate their recovery processes. Therefore, in these cases as well, simplified modeling tools such as publicly or commercially available analytical simulators may provide as much information as numerical reservoir simulation for identifying the EOR potential in a particular reservoir.

The most common approach of analytical simulation is modeling a well pattern (generally five-spot patterns), assuming that the results represent the average performance of a particular reservoir. This method has proven useful for studying reservoirs that lack information or during the evaluation of exploitation plans for reservoirs in the early stages of development, or in analyzing a portfolio of reservoirs in early stages of screening. The second and less often reported approach is the full-field analytical simulation of reservoirs with important lateral and vertical reservoir heterogeneities (fluid saturations, clay content, net pay, pay continuity, etc.) or fields developed in phases.

It is important to note that oil production profiles obtained from analytical simulation are optimistic. Therefore, the estimated recovery predicted by EOR using fast simulation tools must be interpreted with the proper engineering judgment. Even when production profiles are optimistic, projects can be unprofitable. Analytical simulations are excellent ways to screen and rank a portfolio of reservoirs in a short time with a reduced amount of information.

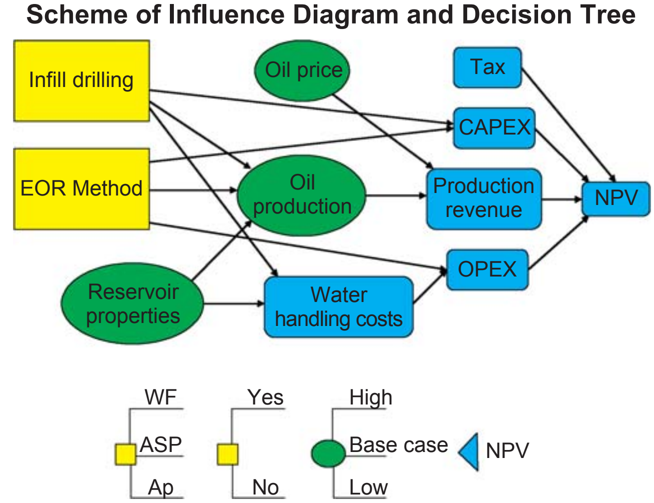
Both analytical and numerical simulations can be linked to commercially available decision-making and risk analysis tools that aid EOR project evaluation. Programs using influence diagrams (IDs) to generate decision trees, tornado diagrams and risk profiles are often used because of their simplicity and compatibility with Microsoft® Excel™, but other options are available that can be considered based on user software preferences and available platforms.

Briefly, IDs are generally built based on value nodes, uncertainty (discrete or continuous) nodes, and decision nodes and the relationships between them. Generating IDs is an important step in simulations, and a multidisciplinary approach is recommended. Figure 5 shows a simplified scheme of an ID and its correspondent decision tree for evaluating a chemical flood in a medium crude oil reservoir. The ID shows value (blue rounded rectangles), uncertainties (green ovals), and decisions (yellow squares) nodes and the relationship among them.

In this case, net present value (NPV) was selected as the objective function, but it can be any variable: recovery factor, incremental cost per barrel, rate of return, etc. Among the uncertainties associated with reservoir properties are net pay, pay continuity, clay content, and water and oil saturations, among others. These uncertainties are evaluated in the analytical or nu-

FIGURE 5

Scheme of Influence Diagram and Decision Tree



merical simulation that estimates oil production profiles used in economic evaluations and ranks the most profitable options.

Economic Evaluations

Given that economic evaluations can vary from company to company, the operator or investor generally develops this step. The economics can be run linked to simulations and decision-risk analysis either by exporting all possible production profiles to commercial software, or by developing the required interfaces in Excel or Visual Basic™. In these cases, the economics are run considering the main input criteria and constraints provided by the operator or investor.

The economic evaluation can also be run using optimistic production profiles and different oil prices for the purposes of screening. If projects are unprofitable or too sensitive under the conditions evaluated, they can be discarded and re-examined during the next planning period. However, later examination will depend on the risk tolerance of the operator or a particular investor for a specific EOR technology. What is important is that an oil reservoir needs to be re-evaluated periodically to determine how current development plans may impact EOR processes in later stages of production because of changes in reservoir conditions. Potential oil recovery is dynamic and changes as a reservoir matures and as reservoir energy evolves.

Finally, the major utility of the methodology is the ability to screen projects very rapidly and then concentrate on the projects that appear to have economic merit. Today's energy prices will likely lead to a greater viability of EOR projects when compared to the past two decades. Therefore, additional economic indicators such as rate of return, net profit, cost per incremental barrel, etc., can be used to rank EOR options in a particular field.

U.S. Carbonate Reservoirs

A comprehensive review of EOR experiences in U.S. carbonate reservoirs over the past four decades was conducted as part of an analysis to identify EOR opportunities in mature carbonate formations in the United States using the systematic methodology. From the review of 139 EOR field projects, it was concluded that:

- Waterflooding combined with infill drilling programs have been the most representative recovery strategies applied during the last three decades.
- CO_2 (water-alternating-gas) has been the most important EOR process since the mid-1980s, and the growing number of CO_2 floods is usually tied to the availability of natural CO_2 sources and transporting pipelines in the Permian Basin.
- Polymer flooding is the second largest recovery process in carbonate reservoirs (1960-1985), but it has made a relatively small contribution in terms of total oil recovered. Most of the projects were developed in early stages of waterflooding, with few successes reported. If chemical methods become an EOR option in the near future, new processes will require the proper design of surfactants, given the maturity of waterflooded carbonate reservoirs.
- The application of EOR processes other than CO_2 and polymer flooding has occurred in a limited number of carbonate reservoirs. However, high-pressure air injection (HPAI) represents a good opportunity to revitalize mature fields. It can be validated by the increased number of projects in the dolomite reservoirs in Montana and North and South Dakota since 2001.

Given their low matrix permeability, carbonate reservoirs seem to represent a case where EOR will continue to be dominated by CO_2 flooding unless improved and more viable EOR strategies are developed in the near future. Therefore, CO_2 projects are expected to continue to grow in carbonate reservoirs, especially in the Permian Basin, because of the availability of CO_2 sources and infrastructure. CO_2 floods in the United States have steadily increased since the early 1990s despite oil prices

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FIGURE 6

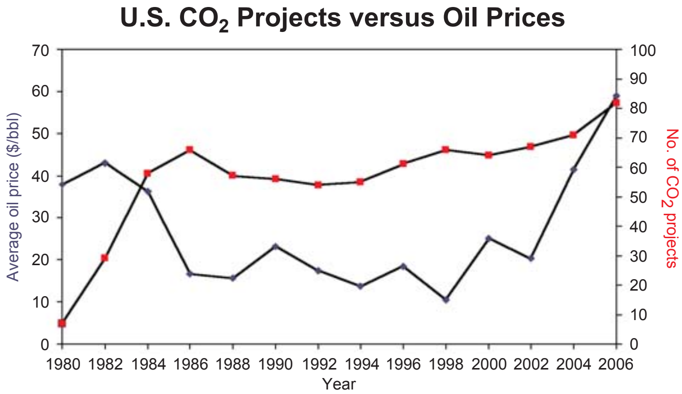
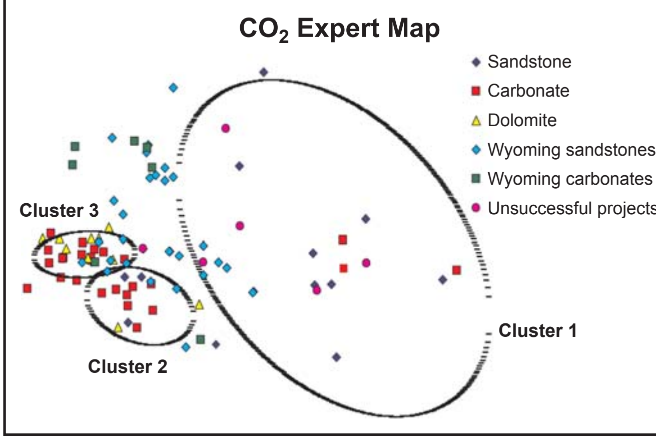


FIGURE 7



of $10-$20 a barrel (Figure 6). The growing interest in CO_2 flooding can be attributed to the maturity of the technology and low CO_2 prices (around $1/Mcf) and low CO_2 utilization factors (<10 Mcf per incremental barrel).

CO_2 Sequestration

However, in areas without access to natural sources of CO_2, the only options are to capture CO_2 from power and petrochemical plants and other sources if it is to be incorporated at competitive prices. With the current oil price scenario and recent initiatives on CO_2 capture and sequestration in the United States, the likelihood that the number of CO_2 projects will increase is high.

That is why some companies in the power generation sector have started technical and economic feasibility studies of CO_2 capture for potential CO_2 EOR projects coupled with geologic sequestration. As part of this effort, CO_2 capture and sequestration has been adapted into the systematic EOR reservoir screening methodology.

The CO_2 modification considers the generation of CO_2 expert maps by consolidating CO_2 field experiences developed in different lithologies (Figure 7). In this case, the expert map was generated with five reservoir variables: API, depth (TVD), permeability, porosity, and reservoir pressure at the beginning of the CO_2 flood.

Figure 7 also shows some of the unsuccessful CO_2 floods, as well as oil field candidates for CO_2 flooding in Wyoming. A preliminary analysis shows that an important number of reservoirs have pressures too low (Wyoming fields at the top left of the figure) or are too viscous to develop miscible CO_2 floods. This analysis is an ongoing effort and will be reported along with the screening methods documented by private companies and universities.

Increased demand and supply shortages have driven oil prices to new highs. That, coupled with the ability to screen projects rapidly, will result in an increase in the number on EOR projects over the next several years. Taking a strategic and systematic approach to screening EOR candidates will help operators make critical decisions early in the evaluation process. ❒

Editor's Note: The preceding article is the first in a series the authors are writing for *The American Oil & Gas Reporter* on EOR technologies and applications. The second article will be featured in the July issue, and will discuss the impact of advanced technology on various EOR processes.