What Is Reservoir Management?

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Summary

This paper describes practical aspects of reservoir management and new approaches being used today, with emphasis on the multidisciplinary team approach. Case studies are presented that illustrate the effectiveness of this approach. In addition, specific attributes of a successful reservoir-management organization and program are highlighted.

Definition

Reservoir management has been defined by a number of authors.[1-4] Basically, sound reservoir-management practice relies on use of financial, technological, and human resources, while minimizing capital investments and operating expenses to maximize economic recovery of oil and gas from a reservoir. The purpose of reservoir management is to control operations to obtain the maximum possible economic recovery from a reservoir on the basis of facts, information, and knowledge.[3]

History and Current Status

Before 1970, many considered reservoir engineering to be of major technical importance in reservoir management. Wyllie[5] emphasized the fundamental concepts of reservoir mechanics and automation with computers. Essley[6] emphasized the advancement in technical aspects of reservoir engineering, yet warned that vital engineering considerations are often neglected or ignored.

During the 1970's and 1980's, synergism between geoscientists and reservoir engineering proved to be very successful. Craig *et al.*[7] emphasized the value of detailed reservoir description with geological, geophysical, and reservoir-simulation techniques. Harris and Hewitt[8] presented a geological perspective of the synergism in reservoir management. Even though the synergism provided by the interaction between geoscientists and reservoir engineering was quite successful, the values of other disciplines (e.g., production operations and drilling) and other engineering functions like facilities engineering were not realized to their fullest extent.

Reservoir management has now matured to the point where great emphasis is placed on working as a crossfunctional team, involving all technical areas, management, economics, legal, and environmental groups. This type of reservoir-management model has proved to be quite successful.[9-20] This paper highlights the major contributions to this model.

Data Collection and Management

Data collection and management are very important to project success, and they must be carefully planned and carried out. A clear understanding of the purpose and application of the data is necessary (i.e., a definition of why the information is needed and how it is to be used). A cost/benefit analysis of the data (i.e., the cost of data collection and management and the benefits to be derived) is mandatory.

Justification, priority, timeliness, quality, and cost-effectiveness should be the guiding factors in data collection and analysis. **Fig. 1** shows an efficient data-flow diagram. Proper timing of data collection is very important because early initiation of a well-coordinated data-collection program not only provides a better monitoring and evaluation tool, but also costs less in the long run. For example, a few early drillstem tests could help decide if and where to set pipe. Sometimes these data can also provide the same type of information normally available by complex and expensive cased-hole, multiple-zone testing. An extra log or an additional hour's time on a drillstem test may provide better information than could be obtained from more expensive core analysis.

A market research found that geologists and engineers spend up to half their time collecting and processing data.[17] As a result, they have less time available for analysis and making future recommendations. The data-management issue is not an easy task. We all look forward to the result of a joint-study project, sponsored by the Petrotechnical Open Software Corp., in developing industry data standards.

Integration of Geoscience and Engineering

In 1977, Halbouty[19] advised, "It is the duty and responsibility of industry managers to encourage full coordination of geologists, geophysicists, and petroleum engineers to advance petroleum exploration, development, and production." Since then, considerable progress has been made in this integration effort.

Sessions and Lehman[20] presented the concept of increased interaction between geologists and reservoir engineers through multifunctional teams and cross training between the disciplines. Sneider[21] recommended that geologists, geophysicists, petroleum engineers, and others work together on a project more effectively and efficiently as a team rather than working as a group of individuals.

Traditionally, data of different types have been processed separately, leading to several disparate approaches: a geologic, a geophysical, and a production/engineering model. The industry has made considerable progress in integrating these models as the importance of geology and geophysics in predicting reservoir performance is better recognized by reservoir engineers. With the advent of 3D geologic modeling programs, automating the generation of geological maps and cross sections from exploration data is practical. In addition, the geologic picture (including the qualitative interferences) is being transferred into a simulation model.[22,23]

Using numerical simulation, the reservoir engineer today seeks more data, both in quantity and quality, from the geoscientists. On the other hand, history matching of the reservoir's performance and utilization of a numerical simulation model can lead to feedback of geological information to the geologist.

Better tools and data, along with the advent of new technology, such as workstations and integrated software packages, can minimize remaining barriers between reservoir-management disciplines. Integrated data-storage and -retrieval systems that use workstations and interactive technologies provide a bridge between geoscientists and engineers. By integrating the work of geoscientists and engineers, it is possible to check and to validate seismic and geologic interpretations. Team members are able to correct contradictions as they arise, minimizing costly errors later in the field's life. In a broader sense, current reservoir-management approaches look not only at integration of geosciences and engineering, but also at integration of data, tools, technology and people, as **Fig. 2** shows.

Geostatistics and Reservoir Characterization

Geostatistics modeling of reservoir heterogeneities is playing an important role in generating more accurate reservoir models. It provides a set of spatial data-analysis tools in probabilistic language that can be shared by geologists, geophysicists, and reservoir engineers (a practical vehicle for integrating various sources of uncertain information).[24,25] Geostatistics is useful in modeling the variability of reservoir properties and the correlation between related properties, such as

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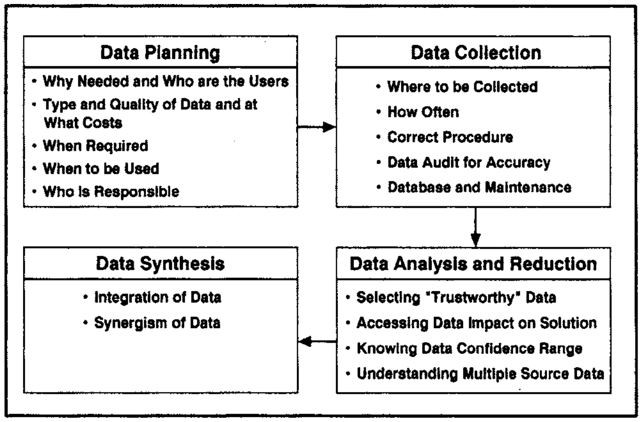

Fig. 1—An efficient data-flow diagram (adapted from Ref. 18).

porosity and seismic velocity. These models can then be used in the construction of numerical models for interpolating a property.

Geostatistics enables geologists to put their valuable information in a format that can be used by reservoir engineers. In the absence of sufficient data in a particular reservoir, statistical characteristics from other more mature fields in similar geologic environments and/or outcrop studies are used. By capturing heterogeneities in a quantitative form, one can create a more realistic geologic description.

Seismic Data

Three-dimensional seismic surveys are playing an important role in identifying reserves that may not be produced optimally. They are used to assist in the design or the development plan.[26-28] As the field development occurs and the development wells are drilled, the added information is used to refine the original interpretation. As time passes and the data build, elements of the 3D data that were initially ambiguous begin to make sense. The usefulness of a 3D seismic survey lasts for the life of a reservoir. Three-dimensional seismic data can be used to assist (1) in defining the geometric framework, (2) in identifying rock and fluid properties, and (3) in flow surveillance. Today, 4D seismic (3D seismic data collected as a function of time) is beginning to yield useful results in monitoring EOR projects.

Crosswell seismic tomography is developing into another important tool, and notable advances have taken place in our understanding of the imaging capability of crosswell tomograms within the last few years. Tomography, which involves selectively obtaining a representation of a predetermined plane section of a solid object, has its roots in medicine. The fundamental concept involved in wellbore tomography is that high-frequency seismic waves, capable of traveling long interwell distances, are generated in one well and the response is observed in one or more neighboring wells. **Fig. 3** shows a typical crosswell geometry.

Current applications of this technology focus on improving our geologic knowledge of the reservoir and monitoring EOR processes. A considerable amount of crosswell tomography has been applied in steamflood operations. It is particularly well suited for this application because the presence of steam in the formation reduces seismic velocity tremendously. Also, for low-gravity oils in unconsolidated sand reservoirs, seismic velocity decreases with increased temperature. As a result, seismic velocities are used as an indicator of high temperatures and/or steam saturations in the reservoir.

The following are some significant advantages of crosswell seismic data over surface data.

1. Both the source and receivers are below the weathered layer, and high-frequency (up to 100 cycles/sec) seismic velocities can be created.
2. Arrival times of directly transmitted waves, the highest amplitude event, are measured, whereas conventional surface data record reflections. Results in the latter case suffer reflection and transmission losses.

There is no doubt that reservoir engineers and geologists are benefiting from seismic and crosshole seismology data. It is equally essential that geological and engineering ideas and reasoning be incorporated into all seismic results if the full economic value of the seismic data is to be realized. Seismologists may overlook a possible extension in a proven area because of their unfamiliarity with the detailed geology and engineering data obtained through development. For this reason, geological and engineering data should be reviewed and coordinated with the geophysicists to determine whether an extension is possible. Robertson[2] points out that the geologic detail needed to develop reservoirs exceeds the detail required to find them. A 3D seismic analysis can lead to identification of reserves that may not be produced optimally and can save costs by minimizing dry holes and poor producers.

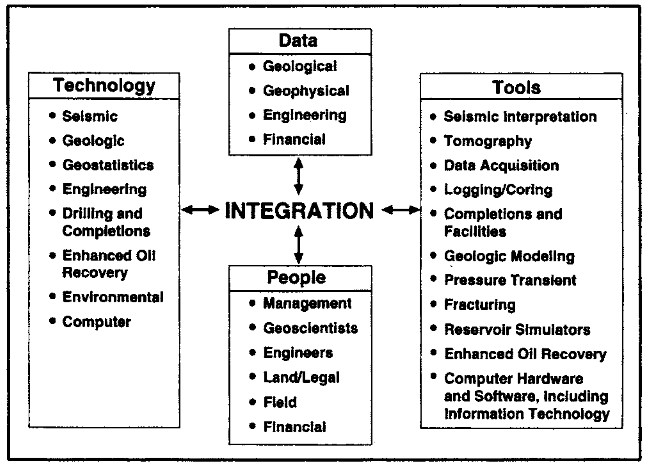

Fig. 2—Reservoir management (adapted from Ref. 4).

Reservoir Geochemistry

Geochemistry is beginning to play an important role in reservoir management by defining reservoir continuity, tubing-string communication, and production allocation and by identifying reservoir fluid. It recognizes that oils from the same reservoir exhibit nearly identical fingerprints, whereas oils from separate reservoirs usually show measurable chromatographic differences. We recently used chromatographic data, production data, and a geologic review that resulted in new structural interpretation in a Gulf of Mexico field

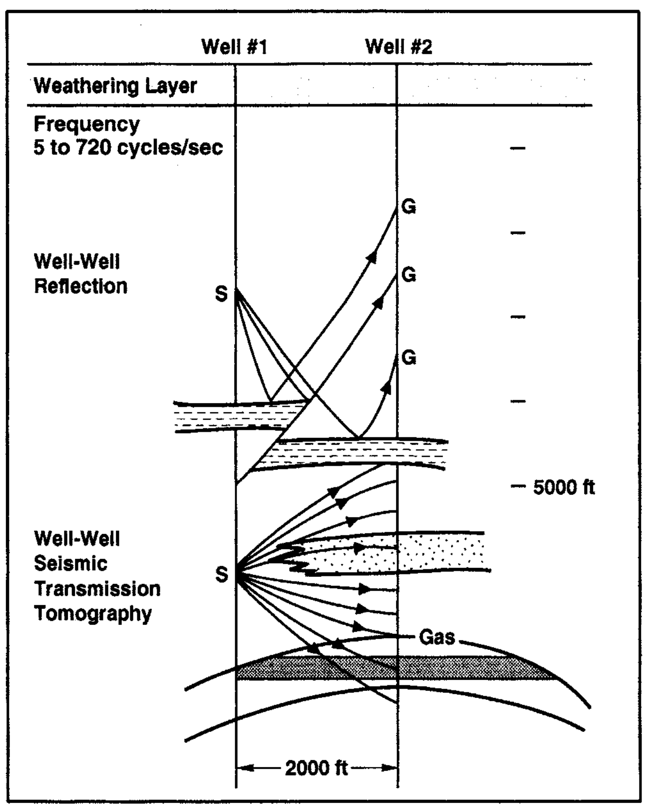

Fig. 3—Reservoir characterization with cross-well seismology (adapted from Ref. 28).

where three fault blocks were mapped rather than two. Because of this, a development well was successfully drilled in a fault block.

In multiple-completion wells, routine geochemical analysis of the produced fluids can often provide early identification of leaks that may not be readily detected by changes in the production history of the well. Gas chromatography plays an important role in determining the proportions of commingled production from various zones in a well. This method is based on mixing curves derived from laboratory mixtures of the end-member oils to determine the relative contributions of individual zones.

Geochemistry is also critical in secondary and enhanced recovery projects (1) by identifying permeability differences in various zones and of thief zones and (2) by recognizing the change in concentration of certain ions in produced water in waterflood projects because of the different chemistries in injection and formation water.

Reservoir Simulation

The economic viability of a reservoir is greatly influenced by the production performance under current and future operating conditions. Today, with the advent of computer hardware and software, simulation studies are much easier and less expensive. In fact, with the availability of software on PC's and graphical user interfaces, reservoir simulation is becoming a common tool for practicing petroleum engineers. Desktop computers and a wide variety of reservoir-simulation systems provide engineers and geoscientists with economical means to solve complex reservoir problems in a reasonable time frame. Today, more emphasis is being placed on graphical user interface, and graphical visualization of results is playing an important role in conducting simulation studies.

For effective reservoir management, the reservoir-simulation model should be developed jointly by engineers and geoscientists for the following reasons.

1. An interplay of efforts results in a more comprehensive description of the reservoir.
2. The team working together can produce an accurate *a priori* reservoir description. In addition, the team can gain invaluable information related to structural and stratigraphic properties by conducting history matching.
3. By combining 3D seismic data with geostatistical information and conducting a reservoir-simulation study, the presence or lack of continuity between wells can be identified, which can improve reservoir description significantly.

Reservoir-simulation models in reservoir management have many educational values. Too often, we demand rigorous determination of all types of input data before accepting the computed results as meaningful. However, the need for accurate input data should always be analyzed critically in the light of the sensitivity of computed results to variations in those data. Sensitivity to errors in reservoir-description data can be determined by performing simulation runs with variations in those data covering a reasonable range of uncertainty. Thus, efforts should be made to obtain those data that have the greatest effect on calculated performances and, in turn, on economics.

A general guide for developing a reservoir-simulation model is to "select the least complicated model and grossest reservoir description that will allow the desired estimation of reservoir performance.[29]" Sometimes in the absence of available data for a relatively new field where limited development may have occurred, it is not uncommon to prepare a simple and generally less heterogeneous reservoir-simulation model. With these concepts, obtaining a history match without substantially changing rock and/or fluid properties generally is difficult.

If a reservoir-simulation model is to be used for making major economic decisions, then it is extremely important to represent the distributions of reservoir and nonreservoir rock types and of reservoir fluids accurately. For example, the number and scale of shale (or dense carbonate) breaks in the physical framework determine the continuity of the reservoir facies and influence vertical and horizontal continuity, which, in turn, influence the dimensions of each cell. Variations in reservoir parameters may require several cross sections or a 3D model.

In the absence of sufficient available data in a particular reservoir, statistical characteristics from other more mature fields in similar geologic environments and/or outcrop studies should be used. By

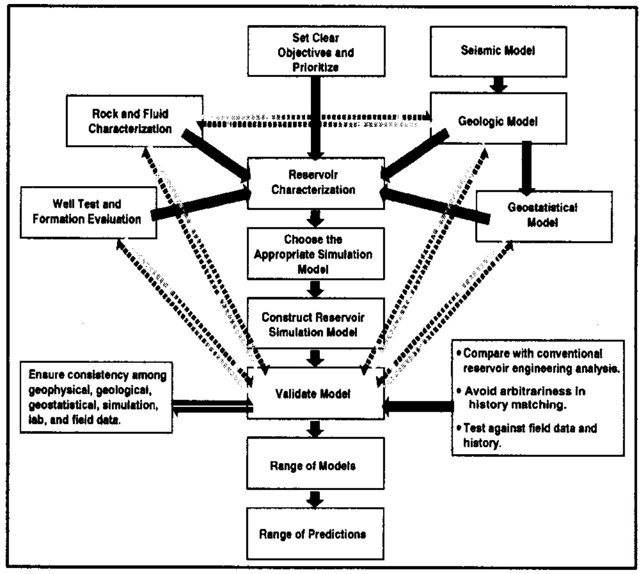

Fig. 4—Reservoir modeling and performance prediction (modified from Ref. 34).

capturing the critical heterogeneities in a quantitative form, we should be able to create a more realistic geologic description in the reservoir-simulation model.

As a result of increasing hardware efficiency, reservoir simulation is moving toward finer-grid models. Current industry experience shows that a fine-grid model combined with geostatistical methods can produce a reliable history match without adjusting rock and fluid properties. This process produces better predictions of future performance.[30,31]

Refs. 32 and 33 document the role of reservoir simulation in reservoir management. In addition, a generalized reservoir modeling and performance prediction method is described, emphasizing the use of a range of models and performance predictions (**Fig. 4**) rather than one model and one prediction.[33,34]

Economics

As defined earlier, the objective of sound reservoir management is to maximize net present value by optimizing the capital investment, operating expense, oil production, and reserves and by using any tax benefits that may be applicable to an operation. Economic optimization is the ultimate goal of reservoir management. The economic analyses and comparisons of various scenarios aid in making the best business decision to maximize profits. Hickman[35] recently presented a rationale for reservoir-management economics, describing the economic aspects of reservoir management as two-fold: "(1) the efficient use of available resources and (2) the maximization of asset value within the context of a company's strategy."

Today, economic analyses are being applied throughout the reservoir-management process. Sensitivity to various parameters [e.g., original oil in place (OOIP), reserves and recovery rate forecasts, capital investment, and operating expense] and other data affecting these parameters on the project/reservoir performance can be determined by performing economic analyses with variations in those parameters, thereby covering a reasonable range of uncertainty. In addition, a "decision-analysis" approach can be followed to establish a hierarchy of various parameters. Then, one can focus on those parameters that make the greatest differences in the economics. This approach enables an operator to concentrate on a few vital features and to address lower-priority items if time and resources are available.

With limited availability of finances, minimizing capital investments and operating expenses has become more important than ever. Field automation and continuous quality improvement are getting more and more attention as ways to reduce operating expenses. Most companies are tightening their capital budgets, at least in U.S. operations, so judicious use of capital funds has become an absolute

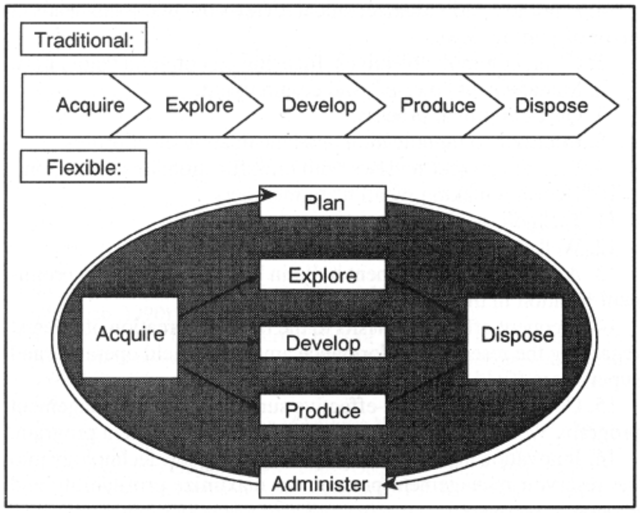

Fig. 5—Traditional and flexible organization (adapted from Ref. 37).

necessity. While cost control is a must, maintaining a high production level is also a must so that revenues are not affected adversely.

Pariani *et al.*[36] provide an instructive example. They studied several active CO_2 floods to determine the optimum near-term cash flow, overall project economics (e.g., rate of return and present worth), and oil recoveries. Injection and production rates, developed by altering specific operating parameters [e.g., gas/water ratio (GOR) and half-cycle slug size], were used in economic analyses to determine the most economical set of operating conditions. The study helped to optimize operations by improving the economics of existing CO_2 floods. It also helped to optimize the CO_2-plant size by adjusting injection schemes to minimize or defer investments while maximizing the economics of new projects.

In early CO_2-flood designs, the plant needed CO_2 reinjection and removal of H_2S and hydrocarbons on the basis of the peak predicted-total-gas production. Because of the single GOR used, the produced-gas rate was expected to increase to some peak and then decline, leaving excess plant capacity. This method required a large plant investment up front, hurting the project economics considerably. With a tapered GOR design, smaller plants with lower capital investments were designed, and the plants operated at a higher efficiency through a major portion of the flood.

Production Operations

Field automation continues to play an increasingly important role in reservoir management. Automation, together with an information management system, is enhancing technical analysis and control. Many companies have created operational data-gathering and -processing systems that are designed to obtain accurate and timely information and to process and condense data. Today's trend is to develop and install automated field systems to monitor a variety of field and plant operations. Automatic well-testing and production-control systems are being used for pumping wells, satellite separation and test facilities, treatment, and storage facilities. In addition, microcomputer-based systems automatically perform pressure-buildup tests in pumping wells from surface measurements and analyze the data in real time at the wellsites.

Team Approach

Reservoir management must include reservoir characterization, fluids and their behavior in the reservoir, creation and operation of wells, and surface processing of fluids. Economical recovery from a reservoir is maximized by an integrated group effort. All pertinent decisions related to management of a reservoir are made by the team considering the entire system, rather than only one aspect. Successful reservoir management requires synergy and team effort. Team members must work together to ensure development and execution of the management plan. By crossing the traditional boundaries and integrating their functions, company resources are better used to achieve the common goal. **Fig. 5** illustrates traditional and flexible organization (i.e., a linear process vs. a flexible and integrated approach). The latter is an integrated organization in which crossfunctional teams focus entirely on work that supports the business objectives. Case studies documenting the actual benefits received from a team approach to reservoir management are described in the next section.

Case Studies

McAllen Ranch Field.[10] This case describes the process of managing redevelopment of a 30-year old geopressured gas field by a crossfunctional team made up of engineers (reservoir, production, petrophysics, and facilities); geologists; geophysicists; field operations personnel; land, permitting, and business/regulatory affairs staff; and tax and legal staff.

The concept of crossfunctional team management became necessary in this case because of declining production and concerns about substantial noncontributing reserves. All team members had compatible and consistent targets. The team had a quasimatrix organization; i.e., all team members remained in their own specialties and had the technical backup and review available, but their actual targets were concentrated on the McAllen Ranch asset team.

Major focus of the McAllen Ranch asset team included a 3D seismic survey acquisition and interpretation, development drilling, commingling (including regulatory approval), field producing operations, and remedial-well work. On the basis of the overall goals, the team developed the following specific targets to be achieved in a 2-year (1990–91) time frame: (1) increase total field gas production rate to > 100 MMcf/D, (2) reduce noncontributing behind reserves by 50%, (3) complete 3D seismic interpretation and mapping and identify at least 10 new drilling locations, (4) reduce drilling costs by at least 10%, and (5) commingle production from various zones. The team achieved or exceeded these targets by the end of the 2 years.

The McAllen Ranch team effort is a well-described example of team excellence. This case study shows that effective crossfunctional teamwork can indeed produce exemplary results for complex oil and gas operations. It also documents that the conventional organizational structure did not function properly and was producing poor results because of conflicting functional goals and objectives.

Brassey Oil Field.[11,12] Woofter and MacGillivary[11] presented a case study of how an aggressive engineering/geoscience team approach provided the development plan for the Brassey oil field in British Columbia. Miscible flooding of the field began only 2 years after discovery. Geological and geophysical contributions to the field development were noteworthy. The interpretation of seismic and offset vertical-seismic-profile data provided the development team with the confidence to drill wells on the edge of the pool. A team approach combined the knowledge from a geological model, seismically defined pool edges, continuity information from well-test data, and material-balance calculations to predict reservoir volume, areal extent, and continuity on the basis of an integrated reservoir model.

The results of the team effort in this field study were tremendous: (1) development of a sound reservoir model; (2) calculation of OOIP by engineering and geologic methods; (3) maintenance of reservoir pressure above the minimum miscibility pressure; and (4) management of production and injection rates by tracer breakthrough monitoring coupled with pressure, voidage, gas compositional analysis, and GOR to minimize breakthrough problems and, in turn, maximize utilization of existing injection compression facilities.

Means San Andres Unit. Stiles and Magruder[13] discussed reservoir management in the San Andres Unit in west Texas from primary to secondary to tertiary operations. The reservoir management in this field started in 1935, just 1 year after discovery. Reservoir management evolved from relatively simple to elaborate techniques because the reservoir had been produced by primary, secondary, and tertiary methods. In addition, the reservoir-management programs included team efforts from several groups and had management support.

A detailed engineering and geologic study was conducted during 1968–69 to determine a new depletion plan. This cooperative study provided the basis for a secondary surveillance program and later for design and implementation of the CO_2 tertiary project. As a result of a joint geology and engineering study, a technique for estimating continuous and floodable pay was developed. This technique assisted estimation of potential additional recovery from infill drilling with pattern densification. About 140 infill wells were drilled through 1981, which would recover > 15 million bbl of incremental oil.

A reservoir study was conducted in 1981–82 that supported a CO_2 flood. Note that the reservoir description conducted in 1968–69 provided the basis for designing the CO_2 flood and was continuously updated as more data and better interpretation became available.

North Ward Estes Field.[14] This case study describes the application of a comprehensive management approach for large and mature reservoirs. The case illustrates the importance and value of team effort, the design and implementation of an EOR project, and the improvement of existing waterfloods.

A study team involving a multidisciplinary team was formed. A reservoir engineer led the team during the design phase, while an individual with operational background led the team during the implementation phase. As a result of the design phase, a design of a six-section CO_2 project was completed. In addition, hundreds of workover candidates were identified and several waterflood modification projects were evaluated. CO_2 injection started in the six-section area within 15 months of project initiation.

Teak Field.[15] This mature offshore field responded very positively to a systematic team approach. The crossfunctional team used a geologist, geophysicist, and reservoir engineer in a study group working closely with operations staff. Detailed structure mapping and reservoir characterization, accurate reservoir models, and good teamwork resulted in two successful development wells in 1989. These wells were completed at 9,000 BOPD, about 25% of the field rate. The team also developed many workovers, recompletion, and waterflood prospects; optimized waterflood patterns; and prepared long-term depletion plans.

Malaysia Fields.[16] An integrated, multidisciplinary team approach has been used in many Esso-operated Malaysia fields. The teams included personnel from operations, surveillance, facilities, reservoir, geology, and geophysics on an as-needed basis. The team members had specific field assignments and worked jointly in acquiring reservoir description data, investigating various operating scenarios, and developing and revising plans.

Apache Intl. Corp. Projects.[17] Some independents, like Apache Intl., have used an innovative team approach to increase production on properties acquired from majors. A full-time interdisciplinary team is assigned one mature acquisition after another to analyze and identify ways to extract additional production. This keeps the team hungry and continuously provides new challenges.

Mitsue Field.[38] The performance of the hydrocarbon miscible flood (HCMF) at this field was optimized by proper monitoring of infill wells, response wells, fluid injection, and observation well performance. In addition, monitoring of operational problems and correcting profile problems by involving various members of different functions resulted in enhanced flood performance. The HCMF has been both economically and technically successful.

Attributes of Successful Reservoir-Management Organization and Program

There is no doubt that these case studies illustrate the benefits of team effort in managing a reservoir. But, an obvious question is, "Can we afford to carry on a full-blown team effort for every project?" Although the answer is no, every team effort should be screened by a cost/benefit analysis.

Identifying specific attributes for all successful teams may be difficult. However, the following list provides items extracted from the case studies in the previous section that made them successful.

1. Early start of reservoir management.
2. Crossfunctional team.
3. Empowerment and reduced routine supervision.
4. Minimum individual technical reviews by functional heads in favor of joint reviews.
5. Clear, common objectives, focusing on common team goals.
6. Management "buy-in" and commitment.
7. Quick approval process.
8. Informal communication and clarification of priorities.
9. Periodic project reviews with crossfunctional participation.
10. Decision making by all team members.
11. Technology transfer between various teams.
12. Well-trained, highly motivated individuals.
13. A reservoir-management bulletin board, mounted in a prominent location in the office and updated monthly.
14. Frequent office staff visits to the field and creation of interest regarding the reservoir performance among the field operators and supervisors (field personnel buy-in and commitment).
15. Comprehensive, cost-effective surveillance and management program. Well-planned data-collection and -management program.
16. Innovation and risk taking by integrating new technology into the reservoir-management program to maximize profitability and economic recovery.

Future Challenges

With limited availability of finances and changing business needs, it will become even more challenging to use capital judiciously and to engage in continuous quality improvement to reduce operating expenses. Field automation, lower maintenance cost, cost control, environment protection, and teamwork will be required for most, if not all, reservoir-management plans. The issue of data management and integration will play an increasing role in the future. Training and technology-implementation efforts will increase, while fundamental R&D may decline. Integrated group effort, empowered decision making, and decision making under a changing economic environment are critical if we want to remain in the oil and gas business. **JPT**

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SI Metric Conversion Factors

bbl × 1.589 873	E − 01 = m^3
cycles/sec × 1.0*	E + 00 = Hz
ft × 3.048*	E − 01 = m

*Conversion factor is exact.

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