PRODUCTION POTENTIAL OF UNRECOVERED MOBILE OIL THROUGH INFIELD DEVELOPMENT: INTEGRATED GEOLOGIC AND ENGINEERING STUDIES - OVERVIEW

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BY:

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FOREWORD

This report is part of a coordinated series of research efforts designed to prepare preliminary evaluations of important components of the domestic unrecovered oil resource. The specific resource of interest is the oil that is displaceable by water and remains in the Nation's reservoirs after conventional production. Integrated geologic, engineering, and economic evaluations in this series estimate future reserve additions from this unrecovered mobile oil (UMO) resource under various circumstances. The individual studies (Volumes 2 through 5) consider the effects of changes in oil prices and advances in production technology on the economic recovery potential of the UMO resource. This report (Volume 1) discusses and compares the approaches and results of the individual studies. Several recovery technologies are evaluated, including the use of waterflooding in conjunction with infill drilling to displace and produce UMO at decreased well spacings.

The overall analysis series was conducted in two separate, but coordinated, parts: at a detailed reservoir level and at a generalized regional level. At the reservoir level, detailed analyses of three individual Texas reservoirs fully delineated the resource and the potential for UMO recovery in each reservoir under a variety of development situations. Results of the individual reservoir evaluations were extrapolated to groups of reservoirs with common depositional histories, collectively known as "plays". At the regional level, reservoirs in three major oil producing states, Texas, Oklahoma, and New Mexico, were analyzed to determine the resource volume, potential recovery, and the costs and benefits associated with this recovery both in the individual states and for the region as a whole. This analysis relied on the geologic classification of individual reservoirs, specific rock and fluid properties, and production and development histories to quantify the resource and to assess its potential for UMO recovery potential. Coordination of the studies at two analytical levels proved advantageous -- the initial methods and results at both levels were compared in order to calibrate and to modify the final approach at each level and can now be used as a guide in future analyses. In addition to the specific results from the two analytical levels, several shorter issue and summary papers have also been prepared.

The individual reservoir and regional analyses reached similar conclusions. The potential for additional production of the UMO resource appears to be established even at low oil prices. At an oil price of $10 per barrel, many reservoirs could be developed to recover significant additional quantities of UMO, even at current levels of technology. However, full exploitation of the UMO resource hinges upon the emergence of efficient methods for characterizing reservoir heterogeneity which would allow accurate assessments of features such as internal architecture, flow paths and barriers to flow. Understanding and describing reservoir heterogeneity would enable the geological targeting of new wells in the most productive portions of the reservoir. Such geologically targeted drilling would increase oil recovery and would lower the oil prices necessary to implement individual projects. Research that refines UMO descriptive and recovery techniques plays a vital role in maximizing the economic production of the resource.

These analyses were conducted by ICF Resources Incorporated, under contracts with the U.S. Department of Energy. Dr. Jerry P. Brashear served as the director of the overall study series. ICF Resources activities were managed by Mr. Michael Godec, who was responsible for the detailed reservoir studies, and Mr. Alan Becker, who managed the three-state regional analysis. Mr. Vello Kuuskraa was the project director for the early development of the methodology and the initial analysis of the Dune Field, the first of the reservoir-specific studies (Volume 2). The Bureau of Economic Geology (BEG) at the University of Texas at Austin served as the principal subcontractor for all analyses, providing critical geologic interpretation, data review, and expert consultation on the analysis and the interpretation of results. Dr. Noel Tyler directed the BEG efforts on these projects.

The staffs of ICF Resources and BEG performed the technical evaluations for the analyses in this series. Mr. Matt Parsley, Mr. Don Remson, and Mr. Jay Rushing of ICF Resources provided critical technical expertise in developing, modifying, and utilizing the methods for analyzing UMO at the reservoir and play levels (Volumes 2, 3, and 4). Ms. Kathleen McFall provided technical evaluations for the early development of the methodology and the initial analysis of the Dune field and South Central Basin Platform Play (Volume 2). Mr. Khosrow Biglarbigi and Mr. Hugh Guinn, in ICF Resources' Bartlesville Office, were critical to the data preparation, methodology development, model updates, and computer analysis completed in the three-state, regional analysis (Volume 5). Mr. Neil Cohen served as researcher for the regional analysis and editor of the final reports. The staff of BEG, including Mr. Bill Ambrose, Mr. Mark Holtz, Ms. Nancy Banta, Mr. Seay Nance, and Mr. Brad Stokes, provided timely and essential support for each of the analyses. Finally, the word processing efforts of Ms. Barbara Jones and Ms. Cheryl LaBrecque of ICF Resources were crucial to the preparation of the reports in this series.

The analyses relied substantially on the data and models that make up the Tertiary Oil Recovery Information System (TORIS). Use of the reservoir information in the TORIS data base was instrumental in completing the regional level analysis and provided an additional source of data for the detailed field studies. This system is maintained by the Bartlesville Project Office (BPO) of the Department of Energy, which also provided computer time for the TORIS regional analysis. Special thanks goes to Mr. R. Michael Ray, the deputy director of BPO, for his technical assistance and critical advice in completing the project.

BEG characterized major oil and gas reservoirs in Texas, New Mexico, and Oklahoma into distinct and separate plays based upon an extensive literature review of depositional systems, trapping mechanisms, structural setting and other geologic information. They assigned heterogeneity factors to each reservoir in the plays, thereby providing a geologic basis for estimating the recovery potential of oil and associated gas recovery for the three-state region. Reservoir data used in the recovery-potential estimates were reviewed and complemented by the BEG staff. BEG also constructed several closely spaced permeability cross sections in the Dune and West Ranch (41-A) reservoirs. BEG and ICF Resources utilized these cross sections to develop pay-continuity functions that were later used in the determination of the volumes of recoverable mobile oil in each of these Texas reservoirs and their associated plays.

Mr. H. William Hochheiser of the Office of Geoscience Research served as the technical project officer for the detailed reservoir evaluations. His timely reviews, input, and technical guidance were essential to the completion of these analyses. Mr. Thomas Wesson, director of BPO, is the technical project officer of the TORIS contract and also provided important suggestions, reviews, and encouragement during the project.

The studies were completed under DOE contracts DE-AC01-85FE60603 and DE-AC19-86BC14000. While acknowledging the assistance of all contributors, errors in fact, analysis, or interpretation are the responsibility of the principal contractor's director and the individual project managers.

Major Reports of the Analytic Series:

- Volume 1 - Production Potential of Unrecovered Mobile Oil Through Infield Development: Integrated Geologic and Engineering Studies - Overview
- Volume 2 - An Assessment of the Reserve Growth Potential of the San Andres/Grayburg Carbonate (South Central Basin Platform) Play in Texas
- Volume 3 - An Assessment of the Reserve Growth Potential of the Frio Barrier-Strandplain Play in Texas
- Volume 4 - An Assessment of the Reserve Growth Potential of the Clear Fork Platform Carbonate Play in Texas
- Volume 5 - Producing Unrecovered Mobile Oil: Evaluation of the Potential Economically Recoverable Reserves in Texas, Oklahoma, and New Mexico

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SUMMARY

Unrecovered mobile oil (UMO) is crude oil that lies in untapped compartments and bypassed zones of reservoirs at the conclusion of conventional recovery. This oil remains unrecovered because of reservoir heterogeneities and differences in mobility between the oil produced and water injected during secondary recovery. Nationally, UMO is estimated to amount to 99 billion barrels -- 20% of all oil ever discovered in the U.S. Unlike "residual" oil, which is immobile to conventional primary and secondary recovery, portions of UMO can be produced by enhancements to conventional recovery methods -- intensive infill drilling and advanced secondary techniques -- if it can first be located within the reservoir. This resource is increasingly acknowledged as a major potential source of future domestic production.

Historically, infill drilling was regarded as a way of accelerating production from a fixed amount of reserves, not of increasing the amount of reserves. More recently, the recognition that geologic heterogeneities in reservoirs cause trapping and bypassing of mobile oil has given rise to the use of intensive infill drilling to increase crude oil reserves. To date, much of this drilling has proceeded on the basis of limited geologic information. It has been hypothesized (Fisher, 1987, Finley and others, 1988) that, with knowledge of the heterogeneity within a reservoir, infill drilling and advanced secondary recovery techniques could produce a significant portion of the UMO resource at relatively low cost by permitting the selective development of the more prolific portions of reservoirs. In addition, advanced secondary recovery techniques to overcome reservoir stratification through profile modification and to overcome unfavorable water-oil mobility through polymer injection could further increase UMO production. This series of coordinated studies was undertaken to evaluate whether the production potential is large enough to warrant further investigation.

The UMO resource was characterized and assessed in detail at the reservoir level in three Texas oil plays (a glossary of geologic terms appears in Appendix B) believed to be promising for UMO development and was examined at the regional level in three major oil producing states -- Texas, New Mexico, and Oklahoma. The economic viability of UMO resource recovery was

examined at several levels of geologic understanding of reservoir heterogeneities available to operators and at several stages of development of advanced primary and secondary recovery technology.

Three different approaches to infill development were examined in both the play and regional analyses: a base case, a selective reservoir-wide case, and a geologically targeted case. Each approach corresponded to an assumed level of geologic understanding of reservoir heterogeneity available to operators. Where geologic information was limited, under the base case, development in each reservoir proceeded with blanket infill drilling to a uniform pattern spacing that was half of current pattern spacing (single drilldown). At a higher level of geologic understanding, the selective reservoir-wide case assumed that the operator would obtain or develop increased information that showed that extensive heterogeneities existed within certain reservoirs but would still have no understanding of heterogeneity on an intra-reservoir scale. Under this case, blanket infill drilling was assumed to proceed to a minimum spacing economically justifiable for each reservoir. The selective reservoir-wide approach would offer the operator information as to which reservoirs would be most economically viable based on some degree of detailed geologic information. At the most advanced level of technology assessed in this analysis, the geologically targeted case assumed that geologic knowledge of intra-reservoir heterogeneities, facies distribution and geometry, and flow boundaries would be identified and characterized by the operator. This advanced level of knowledge would allow strategic development to proceed through the targeting of infill drilling within the most economically prolific portions of the reservoir. In the three-state study, the secondary recovery processes of polymer flooding and profile modification were assessed in combination with infill drilling in each case.

The individual play analyses and the regional evaluation reached similar conclusions. Even at oil prices as low as $10 per barrel, a significant portion of the UMO resource would be economically producible. (Economic evaluations were performed in 1986 dollars in the play-level studies and in 1987 dollars in the three-state study.) At oil prices in the range of $10 to $12 per barrel, base case recovery ranged from 6 to 10% of the UMO resource across the three plays. In the same price range, from 10 to 13% of the UMO resource could be economically recoverable under selective, reservoir-wide development. With advanced geologically targeted development, almost 16% of the total UMO resource could be potentially recovered over the same $10 to $12 per barrel price range. In the two of the three plays in which the geologically targeted case technology was analyzed, 0.6 billion barrels of the 3.7 million barrels UMO resource could be economically produced.

The three-state study results indicated that 3 to 4% of the UMO resource was potentially recoverable under the base case in the $10 to $12 per barrel price range, and that about 9% of the UMO resource could be recovered under the selective reservoir-wide case. As in the play analyses, the reserve additions were maximized through geologically targeted infill drilling, with 11 to 14% of the UMO resource economically recoverable in this price range. With geologically targeted infill development, 3.4 billion barrels out of a total analyzed UMO resource of 24.5 billion barrels would be economically recoverable at $12 barrel.

At $20 per barrel oil price, the three play studies demonstrated that 7 to 13% of the UMO resource could be economically produced under the base case, 16 to 21% could be economically produced under selective reservoir-wide development, and 18 to 24% could be economically produced under geologically targeted development. In the two plays where targeted development was evaluated, over 0.8 billion barrels of the 3.7 billion barrel UMO resource would be economic to produce at this price. Recovery did not increase substantially with higher oil prices in the three plays, however, indicating that most of the recoverable resource was economic at the lower prices in these settings.

Also at a $20 per barrel oil price, the three-state study results showed that 5 to 7% of the UMO target was economically recoverable under the base case, and about 16% was economically, recoverable with selective reservoir-wide infill technology. Advanced geologic understanding used to target prolific portions of individual reservoirs and improve secondary recovery could increase production to 16 to 21% of the UMO resource or up to 5.2 billion barrels in the three states. At even higher prices, substantial additional recovery could be obtained with detailed geologic information and targeted infill development, as up to 28% of the evaluated UMO resource, amounting to over 6.7 billion barrels of oil, was economically recoverable at $36 per barrel.

The results of these studies indicate that improved geologic understanding, geologically targeted infill drilling, and improved secondary recovery techniques can significantly increase U.S. crude oil reserves at low oil prices. These important findings warrant further detailed investigations to determine the optimal techniques for low cost potential UMO recovery. Suggestions for further research, which focus on improving the production of both mobile and immobile oil, are discussed in Appendix A.

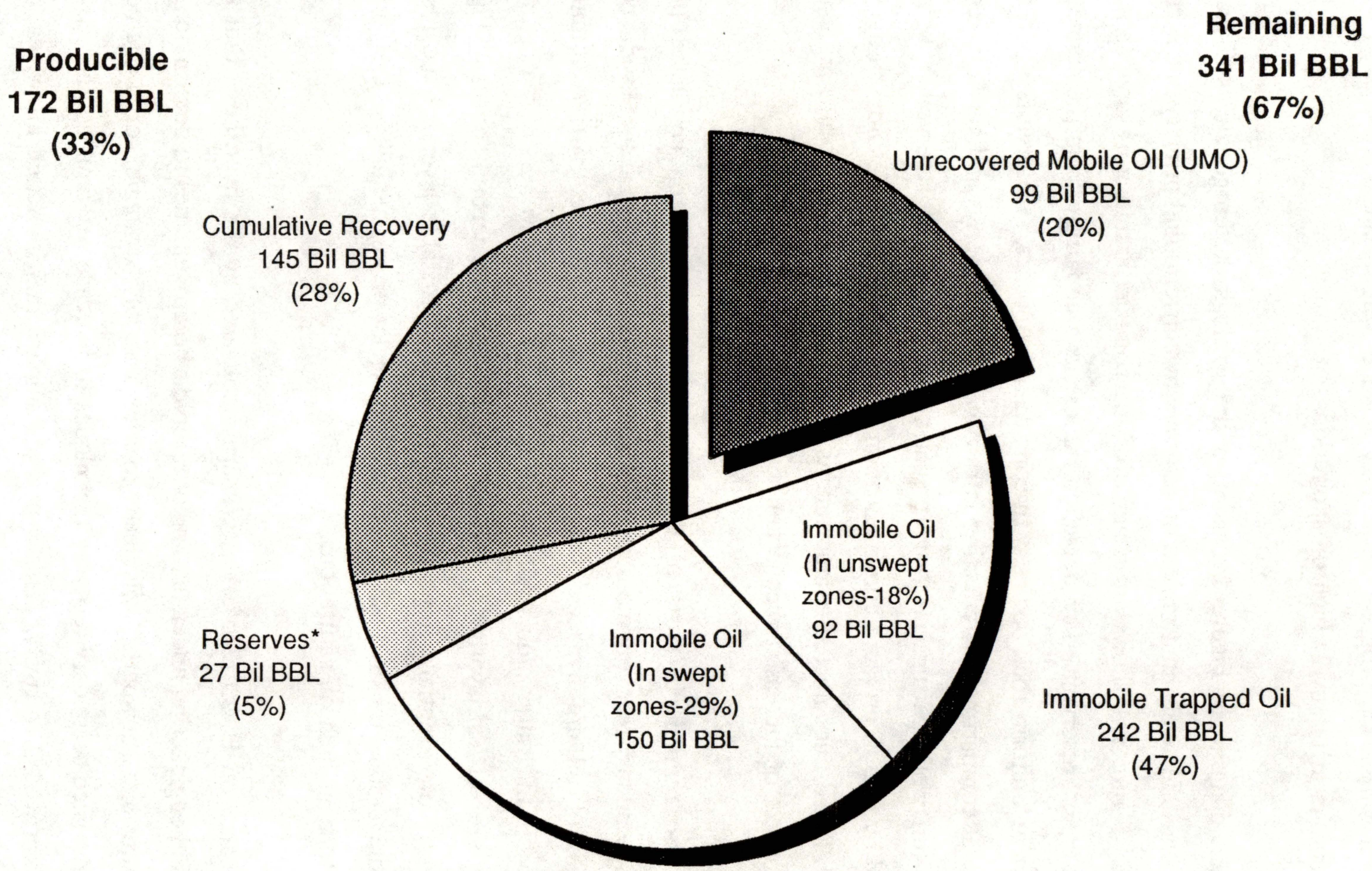
BACKGROUND AND PURPOSE

An estimated 99 billion barrels of unrecovered mobile oil (UMO) in excess of proved reserves remain in known, mature U.S. reservoirs (Figure 1). This resource is displaceable by primary recovery and waterflooding and is the target for intensive infill development and advanced secondary recovery. In addition, 242 billion barrels of immobile oil remain in these reservoirs, with over 88 billion barrels existing in portions of the zones that contain the UMO resource. Recovery of immobile oil requires the injection of chemicals, miscible gases, or thermal energy to overcome the forces that restrict oil recovery.

Mobile oil is left in reservoirs as a result of poor drainage by primary production and inadequate waterflood sweep, both of which result principally from reservoir heterogeneity (Tyler and others, 1984). Reservoir heterogeneity is controlled primarily by the three-dimensional geometry of the reservoir rock which, in turn, is controlled by depositional processes. Other important factors controlling reservoir heterogeneity are post-depositional processes that alter the reservoir-rock properties. Wells drilled at conventional pattern spacings often do not effectively contact all areas of the reservoir; many reservoir compartments remain essentially uncontacted or, if contacted, are bypassed by secondary recovery operations. Uncontacted oil is trapped primarily by areal reservoir heterogeneity and lies in reservoir compartments that are not in communication with wells at the given pattern spacing. Bypassed oil is mobile oil that remains in reservoir strata

Figure 1

Distribution of Known U.S. Oil Resource



Total Original Oil-In-Place
513 Bil BBL

Source: BPO, 1989, API/AGA 1980, EIA 1980 - 87

*Includes proved EOR Reserves

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that is in communication with wellbores. This oil remains unrecovered due to vertical and horizontal permeability stratification and an unfavorable mobility of water relative to oil. Inefficient drilling and waterflood programs, especially at wide well spacings, leave large volumes of mobile oil in reservoirs at relatively high oil saturations.

The simplified diagram in Figure 2 illustrates the geologic heterogeneity and water-oil mobility constraints that effectively limit mobile oil recovery by conventional primary and secondary production methods. Figure 2-A shows an example of the complex architecture now thought to be associated with a typical reservoir. This depiction represents a departure from the conventional concept of reservoirs as uniform rock bodies with consistent properties. Reservoirs often consist of numerous individual compartments, reflecting intra-zonal heterogeneity and varying reservoir properties at a given well spacing. At wider spacings, much of the reservoir may not be effectively contacted by (i.e. in pressure communication with) existing wells, leaving oil at or near original conditions. These uncontacted compartments provide the target for future infill drilling, which offers the prospect of increased recovery at closer spacing.

Mobile oil also remains in parts of the reservoir that have been contacted but not effectively swept by secondary recovery methods. Figure 2-B illustrates that, at large well spacings, considerable volumes of oil are bypassed due to areal variations in reservoir continuity and differences between oil and water mobility in the reservoir. The effectiveness of water injection is further limited by the vertical layering of flooded zones. The cross section shown in Figure 2-C illustrates that water preferentially flows through the more permeable layers of the reservoir, sweeping most of the mobile oil in these layers but leaving lower permeability zones relatively unswept, and therefore, at high oil saturations.

Current research on UMO recovery is primarily motivated by the hypothesis that a more thorough geologic and engineering understanding of reservoir heterogeneities to determine internal reservoir architecture and flowpaths will lead to the use of "strategic" or targeted infill development and advanced secondary recovery techniques to increase reservoir contact, to reduce bypassing, and to improve oil recovery. This hypothesis implies that increased knowledge of

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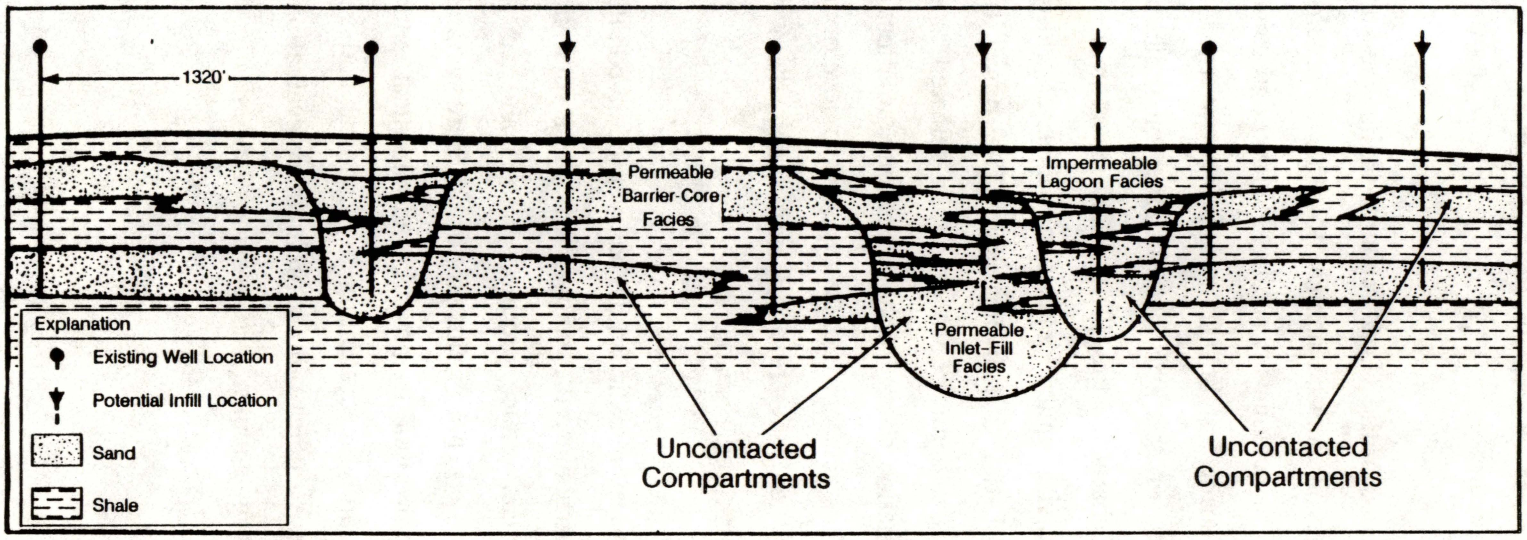
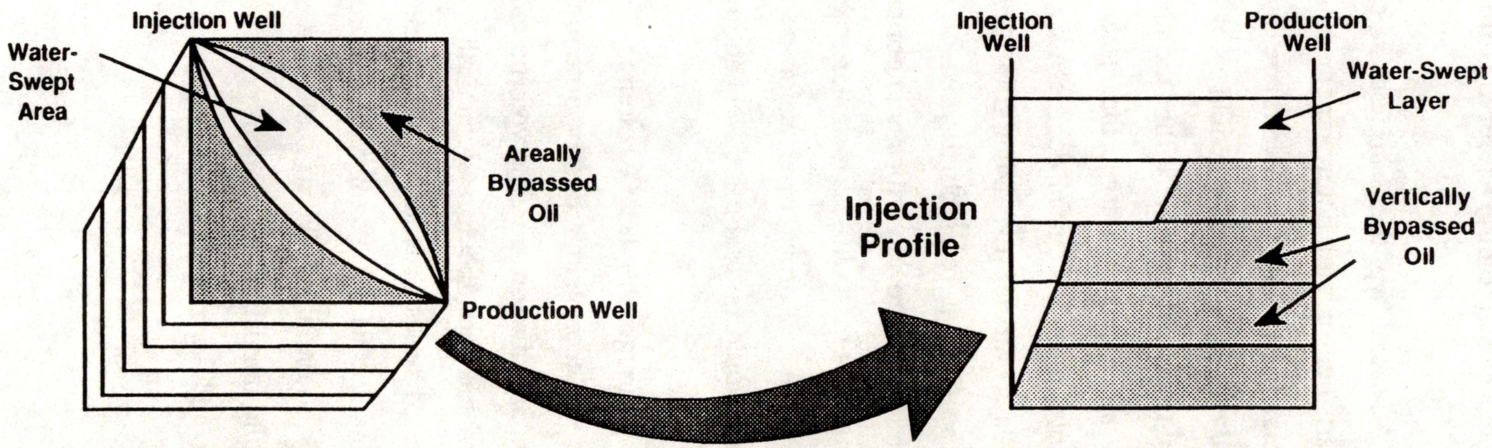
Figure 2

Trapping and Classification of Unrecovered Mobile Oil
Uncontacted and Bypassed Oil Targets



A. Uncontacted Compartments



B. Areally Bypassed Oil
(Within Contacted Compartments)

C. Vertically Bypassed Oil
(Cross-section of Contacted Compartment)

reservoir heterogeneity and its effect on potential recovery must first be pursued at the reservoir level. Indeed, it has been argued that "each reservoir is unique" and thus requires individual study. The time and cost associated with in-depth reservoir evaluations, however, would deter all but the largest and most promising reservoirs from being addressed.

A second hypothesis influencing current views of the UMO resource is that the knowledge gained in the study of heterogeneity in one reservoir may be applied to other reservoirs in the same "play," since these reservoirs are, by definition, geologically similar. Knowledge gained from the study of one reservoir could provide significant insight and could improve the potential recovery from all reservoirs within the play. Moreover, this hypothesis of reservoir similarity could logically be extended to argue that heterogeneity characteristics of a studied reservoir in one play may apply, to a substantial degree, to reservoirs with similar depositional/diagenetic histories in other plays, further expanding the "leverage" of the first hypothesis. The power of these hypotheses is that research focused on a manageable number of carefully selected "specimen" reservoirs could provide critically important information about the heterogeneity, architecture, and flow paths of broad classes of similar reservoirs, thus accelerating their economic development. If these hypotheses prove true, major portions of the UMO resource, not simply the few "best" reservoirs, could be cost-effectively addressed by focused research.

Although the UMO resource is large, no systematic study has yet been conducted to quantify its economic recovery potential. In particular, the central hypothesis that improved geologic information on reservoir heterogeneity can reduce production costs and can increase recovery has not been systematically evaluated. The results reported here summarize a coordinated series of studies which present the conceptual framework and analytical methods for describing the UMO resource in greater detail and for evaluating its technical and economic recovery potential in diverse geologic areas. These studies offer a preliminary evaluation of this potentially important component of domestic energy supplies and provide the basis for deciding whether additional research is warranted.

OVERVIEW OF APPROACH

The overall analytical series was conducted at two separate but coordinated levels -- at a detailed reservoir level and at a more generalized, regional level. At the reservoir level, detailed analyses of three Texas reservoirs defined the UMO resource and recovery potential under several infill development scenarios. These scenarios varied the extent and placement of drilling based on the amount of knowledge of heterogeneity, the level of assumed risk, and the timing of project initiation. Results from the individual reservoir evaluations were used to extrapolate to the plays of which the reservoirs were members. At the regional level, nearly 500 reservoirs in three major oil producing states -- Texas, Oklahoma, and New Mexico -- were individually analyzed to determine the resource volume, potential recovery, and costs and benefits of further development from infill drilling. The three-state analysis also examined the potential recovery possible from the application of advanced secondary recovery processes, which included injection profile modification (reducing the permeability contrasts in the reservoir) and polymer-augmented waterflooding (improving the mobility of water relative to oil). This analysis relied on the geologic classification, specific rock and fluid properties, and production and development histories of the individual reservoirs to quantify the UMO resource and to assess its recovery potential. Results of the individual reservoir evaluations were summed to determine the total regional potential at each oil price and technology level considered. No extrapolation was attempted in the three-state study, and the results represent only the aggregated totals of the specific reservoirs analyzed. Preliminary results obtained at both levels were compared and used to refine analytical methods and to ultimately verify the final results.

CHARACTERIZATION OF RESERVOIR HETEROGENEITY

Reservoir heterogeneity can be characterized quantitatively in the form of continuity functions which relate net pay contact to interwell distance or pattern spacing. Continuous net pay in a reservoir is defined as the volume of hydrocarbon bearing porous rock that is connected between any two wells. The ratio of the continuous porous rock volume to the total porous rock volume between two wells is the fraction of pay continuity between those wells (Stiles, 1976).

Two types of continuity functions, *drainable* and *floodable*, can be developed for different stages of reservoir development. *Drainable pay continuity* is defined as the reservoir volume between two wells that can be drained to a wellbore by primary recovery methods; *floodable pay continuity* is defined as the reservoir volume between the producer-injector pair producible by secondary recovery (waterflood) processes.

The method used in these studies to relate reservoir continuity to potential recovery studies is illustrated in Figure 3 for an example reservoir. As indicated by this reservoir's average continuity curve, 50% of the net reservoir volume would be contacted by wells at a spacing of 40 acres per production well (point A). If the net productive thickness for this reservoir is 100 feet, the zone would behave as having an effective or contacted pay thickness of 50 feet (0.50 x 100 feet) at 40-acre spacing. This net thickness would then be used in the prediction of oil recovery at this spacing.

If the number of injectors and producers is doubled, resulting in a pattern spacing of 20 acres per producing well, the portion of the reservoir effectively contacted increases. This decrease in well spacing increases the effective reservoir contact from 50% at 40 acres to 64% at 20-acre spacing, as determined by moving along the average continuity curve from point A to point B. Infill drilling to 20 acres per producer in the sample reservoir would result in a 28% increase in the effective contacted reservoir volume modeled by adjusting the effective thickness from 50 feet to 64 feet (0.64 x 100 feet).

Geologically targeted infill drilling is conducted by dividing a reservoir into geologically distinct segments. For example, as shown in Figure 3, a geologically simple reservoir can be composed of two segments, a less heterogeneous, more continuous portion and a more heterogeneous, less continuous portion. The net thickness contacted in the two reservoir segments would be described at 40-acre spacing as follows:

- In the less heterogeneous portion (the upper curve), an effective thickness of 75 feet (0.75 x 100 feet) (Point A_1).

- In the more heterogeneous portion (the lower curve), an effective thickness of 30 feet (0.30 x 100 feet) (Point A_2).

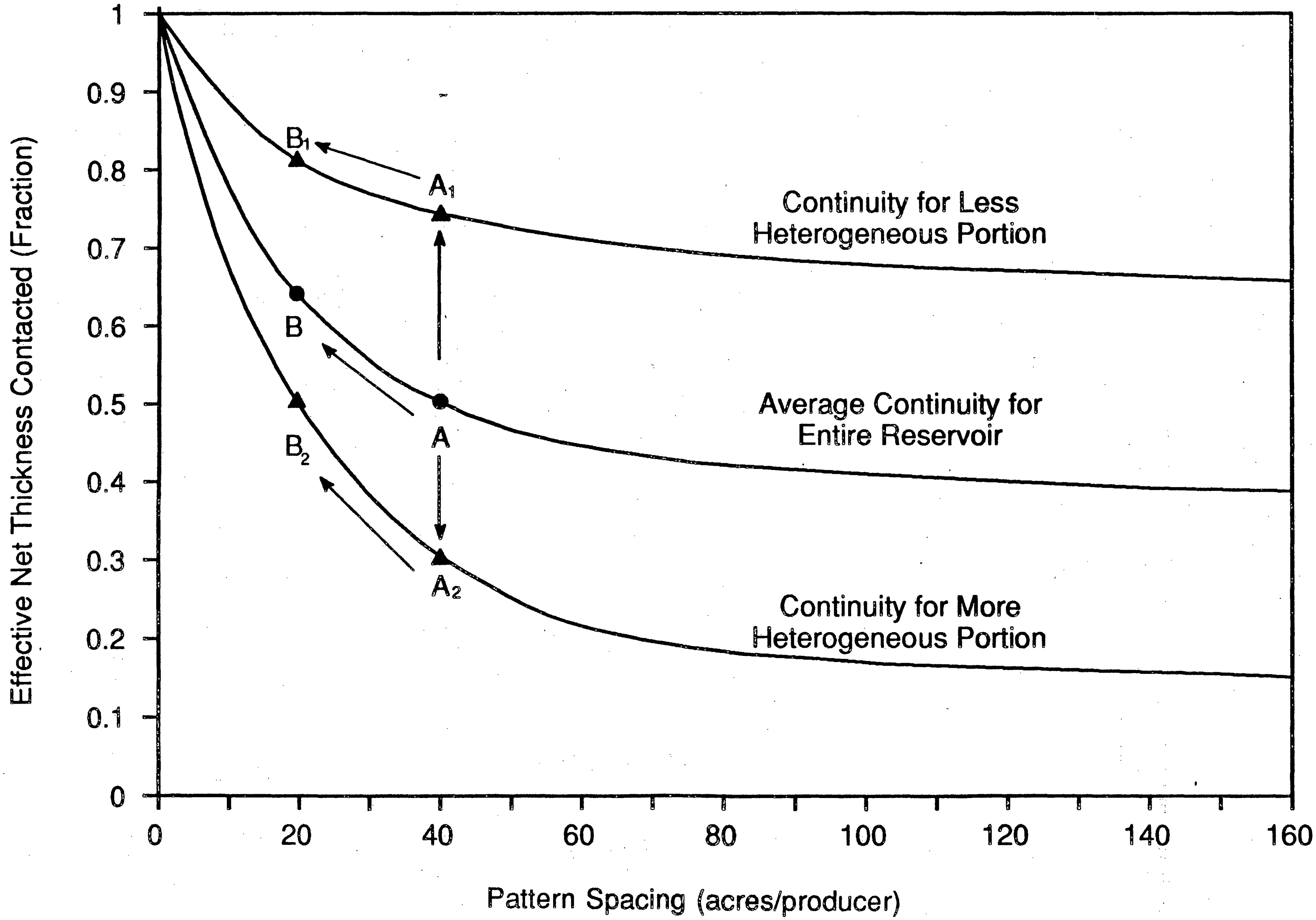
The reservoir can now be evaluated as two separate segments, and correspondingly, two discrete production and economic evaluations can be performed. The decision to implement an infill drilling program is based on the economic attractiveness of production from each segment individually. The additional effective thickness contacted in each segment is determined from the incremental reservoir contact indicated by the continuity curves for the specified segments. For modeling the reservoir described in Figure 3, the effective thickness in the less heterogeneous portion (upper curve) would improve marginally, from 75 feet at 40-acre spacing (Point A_1) to 81 feet at 20 acres per producer (Point B_1). However, the effective thickness in the more heterogeneous portion would increase significantly with the same reduction in average well spacing from 30 feet (Point A_2) to 50 feet (Point B_2). The additional wells required to reduce the spacing by one-half would contact considerably more incremental net pay in the more heterogeneous portion of this reservoir. Clearly, it is the slope of the pay-continuity curve *in the range of well spacing actually being evaluated* that determines which reservoir portion will have the greatest relative increase in effective reservoir volume contacted and a potentially greater response to infill drilling. When pay continuity information is combined with the knowledge of other reservoir properties and the estimated development costs for each reservoir portion, the recovery potential for each discrete portion of the reservoir can be accurately modeled and a thorough economic assessment of the project can be conducted. The relationship between pay-continuity and well spacing, critical to a thorough evaluation of UMO recovery, can be determined only after a detailed geologic analysis of the reservoir has been completed.

DESCRIPTION OF OVERALL METHODOLOGY

The infill drilling approaches used for assessing the recovery potential of the UMO resource were similar for both the reservoir/play analyses and the three-state regional study. First, the recovery potential was examined assuming a blanket or uniform approach to infill development. Second, the recovery potential was evaluated assuming a strategic approach to infill development, identified as the geological targeted case, where the portions of the reservoir with greater infill

Figure 3

Illustration Demonstrating Use of Continuity Functions



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potential were identified and geologically targeted for drilling. Finally, in the three-state regional analysis, the potential of advanced secondary recovery techniques was evaluated for each infill drilling approach.

Two potential approaches for blanket infill development were considered in the analyses. The first approach, which was considered the base case, assumed that a single reduction in waterflood pattern spacing, or one drilldown, would take place at a specific oil price, regardless of the economics of further blanket development. Under this approach, the operator would be unwilling to assume the risk of further development without the acquisition of additional geologic information on reservoir heterogeneity. In the absence of this geologic knowledge, it was assumed that most operators would take a "one-drilldown-at-a-time" approach, delaying dramatically the production response that could potentially result from more intensive infill drilling programs. In the three play analyses, a reduction in spacing from current levels to the next conventional pattern spacing (either 40, 20, or 10 acres per well) was assumed while, in the three-state study, a single one-half reduction in spacing from current levels was assumed.

The second blanket development approach, the selective reservoir-wide case, assumed that infill drilling would proceed in subsequent spacing reductions to the minimum level determined to be economically justified at a specified price. Under this approach, reservoir-wide infill development would be conducted in reservoirs exhibiting significant heterogeneity; however, at this level, no knowledge of intra-reservoir heterogeneities and compartmentalization would be available. This approach assumed that the operator would be willing to accept the risk of continued infill development well beyond the current pattern spacing in certain reservoirs given the collection and analysis of additional geologic information on reservoir-wide characteristics and heterogeneity in these reservoir types. This additional geologic information would reduce the risks associated with infill drilling to close spacing and would allow the operator to quickly assess and to implement drilling activity in highly promising reservoirs.

The advanced geologically targeted case assumed that sufficient geologic data would exist to characterize the reservoir in terms of distinct segments, or facies, with reservoir parameters and heterogeneity relationships developed independently for each segment. Detailed geologic information on intra-reservoir heterogeneity, including facies distribution, facies geometries, and flow boundaries would be available for operators to evaluate the potential oil recovery using targeted infill development, allowing drilling in only the more economically prolific portions of the reservoir. This case represents the most advanced state of technological knowledge and implementation assumed in the play and regional analyses.

Therefore, the three development scenarios are based on three distinct levels of geologic information on reservoir heterogeneity. For each scenario, operators are assumed to be willing to pursue only those infill development projects which are economically viable given the risk commensurate with the level of geologic information available for characterizing reservoir heterogeneity.

The first step in assessing the UMO potential in each set of analyses was to organize the geologically similar reservoirs into plays. Previous work by Galloway and others (1983) classified major oil reservoirs in Texas (those with oil production through 1981 of more than 10 million barrels) into 48 distinct oil plays. Three of the plays indicating significant potential for infill drilling were chosen for more detailed analysis. The three plays selected were the San Andres/Grayburg Carbonate (South Central Basin Platform) Play (19 reservoirs), the Frio Barrier-Strandplain Play (44 reservoirs), and the Clear Fork Platform Carbonate Play (13 reservoirs). Selection of these three plays was based on the combination of their potentially large UMO resource, data availability, potential to serve as analogues for other plays, and contrast in at least two of the following characteristics: lithology, depositional nature, stratigraphic horizon, and regional distribution. One reservoir for each play, was selected to be the representative reservoir for that play. The selected reservoir exhibited average characteristics for the play, and had sufficient data available for detailed analysis. Given unique reservoir property data available for other reservoirs in the play, the results from the detailed analysis of the selected reservoir were then extrapolated to the other reservoirs in the play. The basis for the extrapolation was the assumption that the reservoir selected was, on average, representative. Verification of this assumption was beyond the scope of this study.

In the three-state study, the oil reservoir data base developed as part of the Tertiary Oil Recovery Information System (TORIS) was utilized. The TORIS data base, which contains rock and fluid properties for each reservoir, was upgraded with additional geologic information, including the assignment of individual reservoirs to plays, and individual plays to geologic types. Each reservoir in the three-state study was analyzed separately, based on its unique properties.

The second step in the reservoir/play and state/regional analyses was the development of reservoir data and analysis methods to characterize heterogeneity and the recovery potential of the UMO resource analyzed. In the individual play studies, closely spaced cross sections, facies-specific reservoir data, and historical development and production data were used to develop reservoir continuity versus well spacing functions for the representative reservoirs, relating effective contacted reservoir volume to pattern spacing. In the three-state study, the development and production histories of reservoirs in the TORIS data base were supplemented with heterogeneity rankings for each play to develop continuity functions for specific categories of reservoirs. The reservoir continuity functions were developed by relating mean areal sweep efficiency to well spacing for all reservoirs with similar heterogeneity rankings.

The third step for both analyses was the determination of technically recoverable crude oil and associated gas. This step consisted of two parts: the determination of primary and waterflood oil recovery that would result if there were no further infill development; and the determination of the incremental oil and associated gas that would be recovered by additional infill drilling from current spacing to a minimum level. The latter calculation was made based on the continuity relations and reservoir data established for the representative reservoirs. The technical recovery potential from blanket development was estimated by using average reservoir properties and the reservoir-average continuity functions. Similarly, the technical recovery potential of strategic, or targeted, infill development was estimated by using continuity functions and reservoir properties specifically delineated for distinct reservoir segments or facies.

In the three detailed play analyses, primary production was estimated using standard decline curve analyses. Waterflood production in these analyses was estimated using a simplified waterflood model based on Craig (1973). In the three-state study, recoverable oil from primary and secondary recovery was also estimated from a decline curve analysis. A model based on Buckley-Leverett fractional flow (Buckley and Leverett, 1942) was used in this study to assess ultimate waterflood production, both alone and in combination with injection profile modification and polymer flooding techniques.

In the fourth step, economic and financial analyses were conducted to establish the costs and economic feasibility of oil recovery under the alternative development approaches. Discounted cash flow models with recently validated costs were used in all cases. In the three reservoir/play analyses, the economic evaluation for the representative reservoir consisted of solving for the minimum oil price required to economically implement the infill program and to achieve a 10% real (inflation adjusted) return on investment. In the three-state study, a cash flow analysis was performed for individual development projects in each reservoir for the seven oil prices and two technology levels considered, solving for the after-tax rate of return for each case. Projects achieving a real rate of return exceeding 10% were considered economic at the specific oil price.

Finally, the results of the economic evaluations for each of the individual reservoirs analyzed were aggregated to the play or regional level. In the three play analyses, the specific volumetric and fluid flow characteristics for each reservoir (such as net pay, saturations, and permeability) and for each major facies within the reservoir were combined with representative continuity functions to estimate reservoir-wide and facies-specific recoverable oil. Economic recovery at a given price for every reservoir analyzed in each play was determined based on the recovery efficiency achieved at that price for the representative reservoir. However, to account for the economic effects of variations in permeability for different reservoirs in the plays, the economic viability of the representative reservoir for each play was evaluated assuming varying values of permeability. The economic results for the different permeability cases for the representative reservoir were then extrapolated to estimate the economic performance of reservoirs in the play with similar permeability values. Although variations in other properties for reservoirs (in addition to permeability) would clearly affect project economics, sufficient data were not available to analyze the differences in economic viability pertaining to these properties. The results of the economic analyses for each of the reservoirs in the play were combined to establish the economic potential of each play.

In the three-state rock and fluid, a number of reservoir properties were available for each of the 500 reservoirs, including oil and water saturations, formation volume factors, injection and production volumes, and porosity and permeability. The reservoirs and their unique properties were analyzed individually to determine their technical and economic recovery potential with selected application of the recovery processes evaluated. The results were aggregated to estimate the overall regional UMO recovery potential and are reported only for the reservoirs analyzed; no attempt was made to extrapolate these results to the entire UMO resource in the three states.

OVERVIEW OF RESULTS

The two studies were performed under a consistent conceptual framework and set of fundamental assumptions. However, specific details in the two methods differed for reasons of data availability and other constraints dictated by the structure and format of the existing analytical systems. Despite these differences, the individual reservoir and regional analyses reach highly similar conclusions. The most significant finding is that at prices as low as $10 per barrel, many reservoirs can be developed to recover significant additional quantities of UMO. The results of each study indicate the importance of the successful development of refined UMO descriptive and recovery techniques. Of particular importance is the development of practices where the most productive portions of reservoirs are geologically targeted for infill development. Geologically targeting infill drilling within individual reservoirs could substantially enhance project economics and could lead to improved recovery potential. Full economic exploitation of the UMO resource hinges upon the emergence of such methods that will enable increased oil recovery to be achieved at lower cost.

In addition, the three-state study demonstrated that while intensive infill development could lead to the recovery of large amounts of UMO, improved secondary recovery techniques could also recover significant additional quantities of crude oil, even at relatively low oil prices. Injection profile modification (permeability contrast reduction) and polymer-augmented waterflooding are two currently applied processes showing the most promise. Both processes increase the volume of reservoir rock which is effectively contacted and swept by conventional secondary recovery practices, thus allowing additional oil to be displaced. The applicability of the three techniques analyzed in the three-state study, individually or in combination, depends on the properties and development history of the specific reservoir.

More detailed summaries of the methods and results of individual reservoir/play studies and the three-state analysis are presented in the following sections.

SUMMARY OF THE RESERVOIR/PLAY STUDIES

SUMMARY OF METHODS

Three major Texas oil plays -- the San Andres/Grayburg Carbonate (South Central Basin Platform), the Frio Barrier-Strandplain, and the Clear Fork Platform Carbonate -- were investigated in detail. Chronologically, the studies were performed in the order presented; important since methodological refinements and further insights were gained as the work on this effort preceeded. In each play, an individual reservoir considered to be representative of the rest of the reservoirs in the play was selected for detailed analysis. Closely spaced cross sections for the reservoir were developed using core data, geophysical logs, production data, and development history. This information, in conjunction with geologic analyses, was used to determine the lateral continuity of and vertical communication among productive reservoir zones at various interwell distances (pattern spacings).

The three plays investigated represent three distinct depositional systems, resulting in unique characterizations of reservoir architecture and heterogeneity. The unique character of each play is supported by differences in reservoir properties, characteristic facies types, and geometry and extent of facies. For example, most of the oil production in the carbonate reservoirs of the San Andres/Grayburg Carbonate (South Central Basin Platform) Play is from shallow-marine shelf grainstone bars (Bebout and others, 1987), whereas the clastic reservoirs of the Frio Barrier-Strandplain Play produce primarily from three major facies -- barrier core, tidal inlet fill, and marginal back-barrier (Galloway and Cheng, 1985). In the Clear Fork Platform Carbonate Play, the primary producing facies is a shelf-margin oolite grainstone bar (Mazzullo, 1982). Although the Clear Fork grainstone bars are similar in origin to those of the San Andres/Grayburg Carbonate Play, depositional cycles during Clear Fork time were shorter in duration, resulting in pay stringers which are much thinner and less continuous than those in the San Andres/Grayburg Play.

For the representative reservoirs in the San Andres/Grayburg Carbonate and Frio Barrier-Strandplain Plays, pay-continuity functions were developed and reservoir parameters were established both for the entire reservoir and for each major facies within the reservoir. The facies-specific functions made it possible to economically evaluate the strategic placement of infill wells in each facies in order to identify those facies with the greatest development potential. The potential of strategic infill development of the reservoir was compared to that obtained from blanket infill drilling.

Estimates of the recoverable oil and associated natural gas for each reservoir and for each facies within each reservoir were determined from the appropriate continuity functions and key physical properties, using conventional reservoir engineering techniques. For each case, the potential for both primary and waterflood oil recovery was determined. Incremental recoverable oil from primary operations was determined from the representative reservoir's drainable continuity function, while the recoverable oil from waterflood operations was determined from the reservoir's floodable continuity curve. The estimate of recoverable oil from waterflood operations also reflected the reservoir's waterflood sweep efficiency. Waterflood sweep efficiency is a function of vertical and areal heterogeneity, water-oil mobility, and the quantity of fluid injected and was determined based on history matches to past reservoir production. Oil saturations in the swept portion of the reservoir were assumed to be residual, with the immobile oil saturation in each reservoir determined based on evaluations of core flood tests.

Economic and financial analyses were used to establish the costs and economic feasibility of production under the base, selective reservoir-wide, and geologically targeted cases. The infill program was initiated at different points in the life of a project for each approach. The resultant optimal development scenario in each representative reservoir was extrapolated to the entire field analyzed and then to the other reservoirs in the play.

Finally, volumetric reservoir data, historical development and production data for each reservoir in the play, and the pay-continuity functions established for the representative reservoir were used to establish the UMO target for infill development for each reservoir in the play. The economic analysis of the representative reservoir was used to estimate the economic recovery potential for both the blanket and strategic infill development of the other reservoirs in the play, with the exception of the Clear Fork Platform Carbonate Play, where only blanket infill drilling was considered. This was accomplished by adjusting recovery estimates in the other reservoirs based on their demonstrated production histories and unique rock and fluid properties. The results of the analysis of the other reservoirs in each play were combined to establish the potential of the play.

DISCUSSION OF RESULTS

The results of the analyses for each of the three plays are summarized in Table 1. These plays contained a total of over 19 billion barrels of original oil in place (OOIP). Nearly 11 billion barrels of this OOIP are considered mobile and, therefore, potentially recoverable by primary and secondary recovery techniques. The UMO target in these plays is the original mobile oil in place less the estimated ultimate recovery from conventional technology at current spacing (approximately 6 billion barrels), which amounts to about 5 billion barrels. Of this, approximately 1.2 billion barrels are estimated to be technically recoverable by infill drilling from current pattern spacing to 10 acres per producer in the major reservoirs of the three plays.

In these three plays, 350 million barrels (MMB), or 7% of the 5 billion barrel UMO target, would be potentially economically recoverable under base case development at $10 per barrel, assuming one drilldown, or a single blanket reduction in well spacing in each reservoir from current levels to the next conventional pattern spacing (40, 20, or 10 acres per well). In the selective reservoir-wide case, development to the minimum spacing economically justifiable (down to a minimum level of 10 acres per producer) could result in 495 MMB, or 10% of the UMO target, being economically recoverable at $10 per barrel. At $20 per barrel, 500 MMB, or 10% of the UMO target, could be economic to develop under the base case, while 825 MMB, or 16% of the UMO target, could be economic to produce under the selective reservoir-wide.

Under the geologically targeted case, infill development of the San Andres/Grayburg Carbonate (South Central Basin Platform) and the Frio Barrier-Strandplain Plays, as shown in Table 1 and Figure 4, could result in significant increases in economic recovery. In the San Andres/Grayburg Play, from 16 to 18% of the UMO target could be economic to produce with geologically targeted development at oil prices between $10 and $20 per barrel. Only 6 to 7% of the UMO target could be economically produced at this price in with base case conditions, while from 10 to 16% of the UMO target could be recoverable assuming selective reservoir-wide, development. In the Frio Barrier-Strandplain Play, from 17 to 24% of the UMO target could be economically produced under geologically targeted development at prices between $10 and $20 per barrel. Over this price range, only 5 to 7% of the UMO target could be economically produced under base case conditions, while from 13 to 21% of the UMO target could be recoverable from selective reservoir-wide infill drilling.

Therefore, geologically targeted infill development, designed to exploit the discrete facies within the reservoirs in these plays, significantly enhances the economic potential of UMO recovery. In addition, geologically targeted infill drilling projects can be implemented at lower oil prices, and the recovery potential of targeted drilling, compared to less efficient blanket development, is thus substantially larger.

Table 1

Summary of UMO Recovery Potential in Three Major Texas Oil Plays*

(All Crude Oil Values in Millions of Barrels)

	San Andres/Grayburg (South Central Basin Platform) Play		Frio Barrier-Strandplain Play		Clear Fork Platform Play		Total of Three Plays	
Original Oil in Place	10,417		4,184		4,449		19,095	
Original Mobile Oil in Place	5,652		2,673		2,246		10,571	
Estimated Ultimate Recovery by Conventional Means	2,825		1,763		925		5,513	
UMO Target	2,827		910		1,321		5,058	[3,737**]
Bypassed	1,591		48		282		1,921	
Uncontacted	1,236		862		1,039		3,137	
Remaining Recoverable Infill Oil to 10 Acre Spacing	624		263		308		1,195	
Economically Recoverable at $10/Bbl								
Base Case	165	(6%)	90	(10%)	95	(7%)	350	(7%)
Selective Reservoir-Wide	285	(10%)	115	(13%)	95	(7%)	495	(10%)
Geologically Targeted	440	(16%)	155	(17%)	n/a		595	(16%)**
at $20/Bbl								
Base Case	210	(7%)	120	(13%)	170	(13%)	500	(10%)
Selective Reservoir-Wide	465	(16%)	190	(21%)	170	(13%)	825	(16%)
Geologically Targeted	505	(18%)	215	(24%)	n/a		810	(22%)**

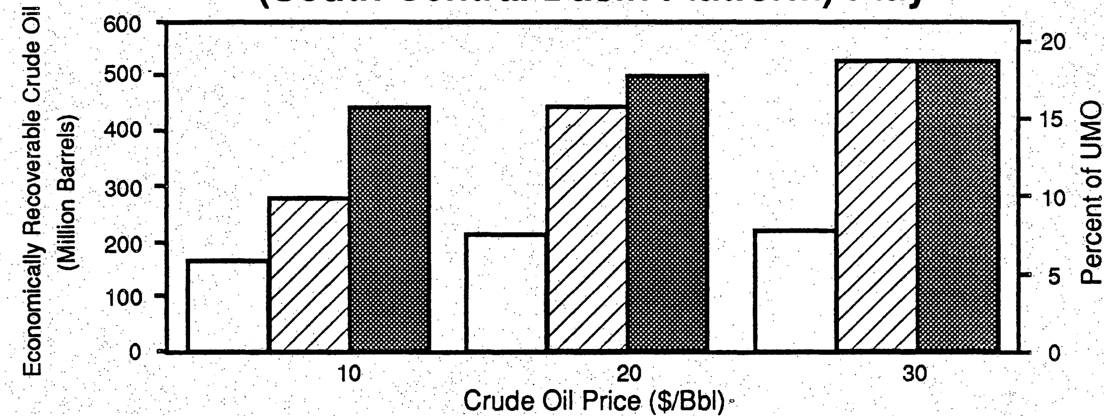
*Percentages represent the fraction of the UMO target that is economically recoverable at that price and level of development.

**Totals are for only the two plays where the strategic infill development potential was evaluated.

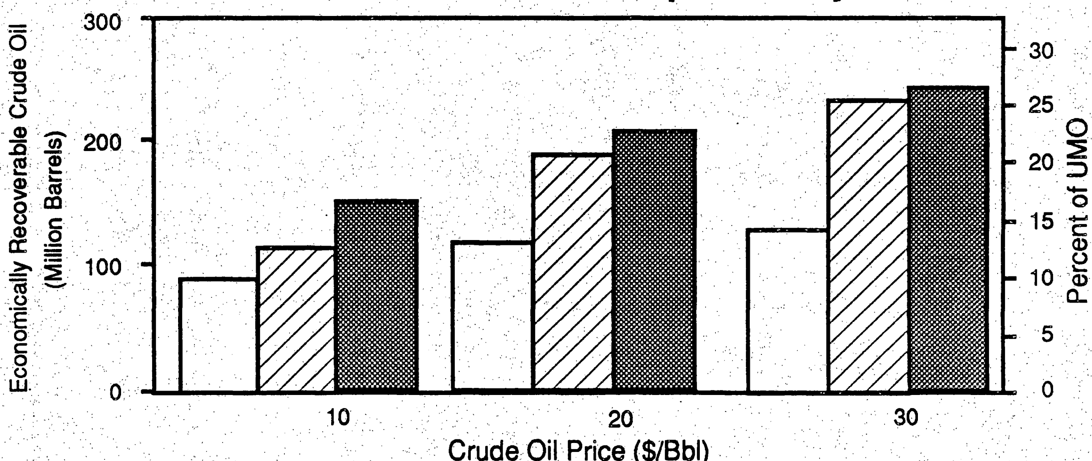
Figure 4

Summary of the UMO Economic Recovery Potential for the Three Texas Oil Plays

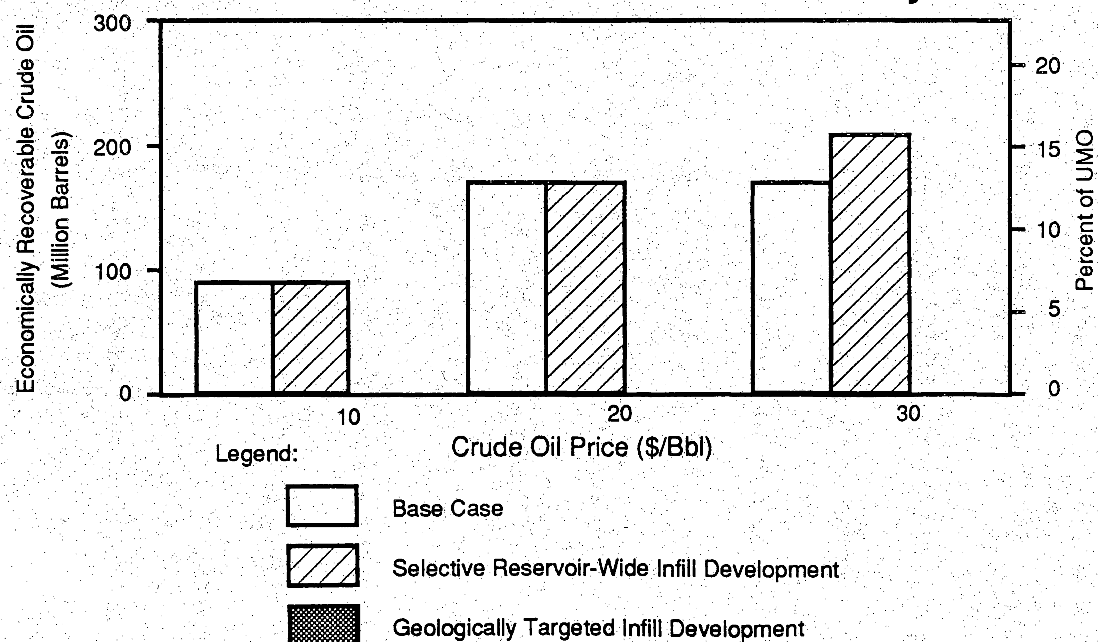
San Andres/Grayburg Carbonate (South Central Basin Platform) Play



Frio Barrier - Strandplain Play



Clear Fork Platform Carbonate Play



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Results for the three plays also show that the timing of the infill program, in terms of the reservoir's stage of development, is critical to the economic success of infill drilling projects. The implementation of infill drilling early in a reservoir's development increases recoverable reserves and accelerates production. Delayed implementation, particularly until after a reservoir has been fully depleted, increases overall per-barrel recovery costs and leads to lower economic oil production levels.

San Andres/Grayburg Carbonate (South Central Basin Platform) Play

The San Andres/Grayburg Carbonate (South Central Basin Platform) Play is a collection of 19 carbonate reservoirs in the Permian Basin of West Texas. The representative study area selected for this play was the 640-acre Section 15 within the Dune field. The location of the play in Texas and the Dune field within the play are illustrated in Figure 5.

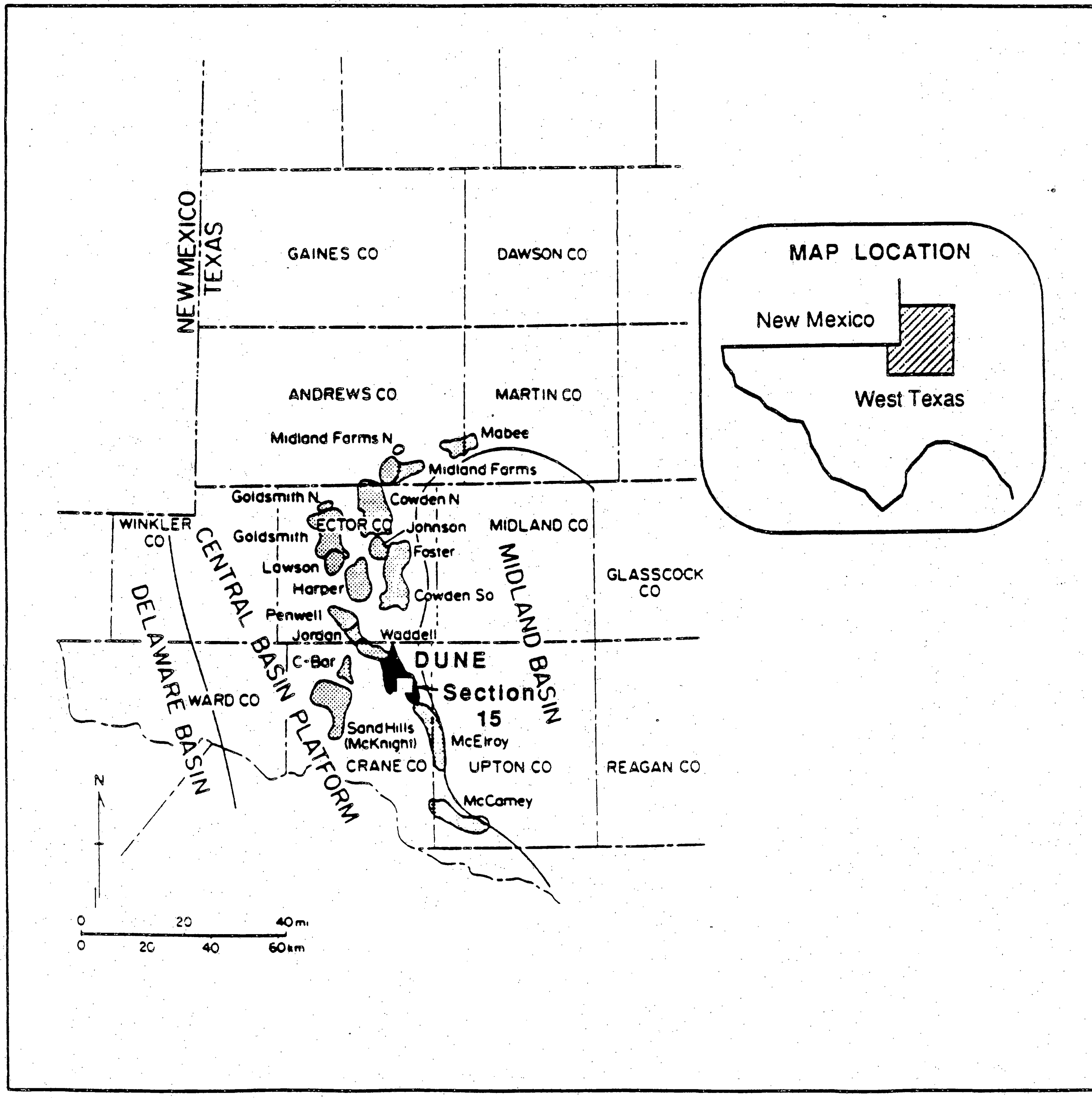
Carbonate strata of the producing San Andres and Grayburg Formations that make up the reservoirs in the play were deposited along the eastern margin of the Central Basin Platform during Permian time in a semi-restricted, platform-margin setting. Relative sea level fluctuations were common during deposition and resulted in the alternating landward and seaward shifting of depositional environments and associated facies tracts for many miles on the low-relief platform. During high sea level periods, subtidal carbonate oolite and skeletal grainstone bars accumulated on the shelf. During periods of low sea level, mixed clastic and carbonate arid tidal-flat deposits migrated basinward over the subtidal deposits. Repeated episodes of relative sea level fluctuations resulted in stacked, cyclic sequences of interbedded shallow-marine and arid tidal-flat deposits.

The main reservoir facies in the San Andres/Grayburg Carbonate Play are dolomitized grainstone bars consisting of oolites and skeletal grains with leached secondary porosity. These reservoir facies pinch out laterally into low-porosity fusulinid wackestones and mudstones and are bounded on the landward side and overlain by non-productive, anhydride-cemented arid tidal-flat facies. Although oil is present in a few vugs in the non-porous tidal-flat facies, no significant volume of hydrocarbons has been found in these facies (Bebout and others, 1987).

Figure 5

Location of San Andres/Grayburg Carbonate (South Central Basin Platform) Fields, Dune Field and Section 15 Study Area

(after Galloway and others, 1983)



Most traps in the play are combinations of structure and stratigraphic features. Structural traps in the play consist of drape closure and offsets along northwest-trending faults which resulted from Pennsylvanian tectonic activity on the platform margin (Galley, 1958; Ward and others, 1986). Stratigraphic trapping also plays a role, as permeable facies pinch out locally.

Because of the depositional cyclicity that occurred on the Central Basin Platform, San Andres and Grayburg reservoirs are highly stratified. In addition, depositional system complexities resulted in a heterogeneous areal distribution of the productive grainstone bar facies. Consequently, the reservoirs typically contain many individual permeable layers commonly less than 15 feet thick that pinch out abruptly from well to well. Recovery efficiencies in the play are typically low, averaging 26%, because of poor lateral and vertical reservoir continuity and weak solution-gas drives. Large, unitized waterfloods or gas-injection programs have been instituted in all of these reservoirs (Galloway and others, 1983).

Four carbonate zones in Section 15 of Dune Field, designated by Bebout and others (1987), collectively contained approximately 30 million barrels of original oil in place distributed in net pay ranging from almost 40 feet to over 160 feet thick. Depositional cyclicity resulted in a complex distribution of facies in Section 15. Because permeability varies with facies type in Section 15, a complex distribution of permeability also occurs, as shown in the cross-section in Figure 6. This type of complex distribution is typical of reservoirs within the San Andres/Grayburg Carbonate (South Central Basin Platform) Play.

A northwest-southeast trending belt of net pay averaging over 130 feet occupies the central part of Section 15 and corresponds to a facies tract dominated by productive grainstones with an average porosity of 11.5%. In contrast, the northeast and southwest corners of Section 15 contain less than 100 feet of average net pay within a nongrainstone facies (mudstones and wackestones) with an average porosity of only 8.8%. Geologic and engineering analyses clearly indicate that oil and gas recovery potential is substantially greater in the grainstone belt in the section.

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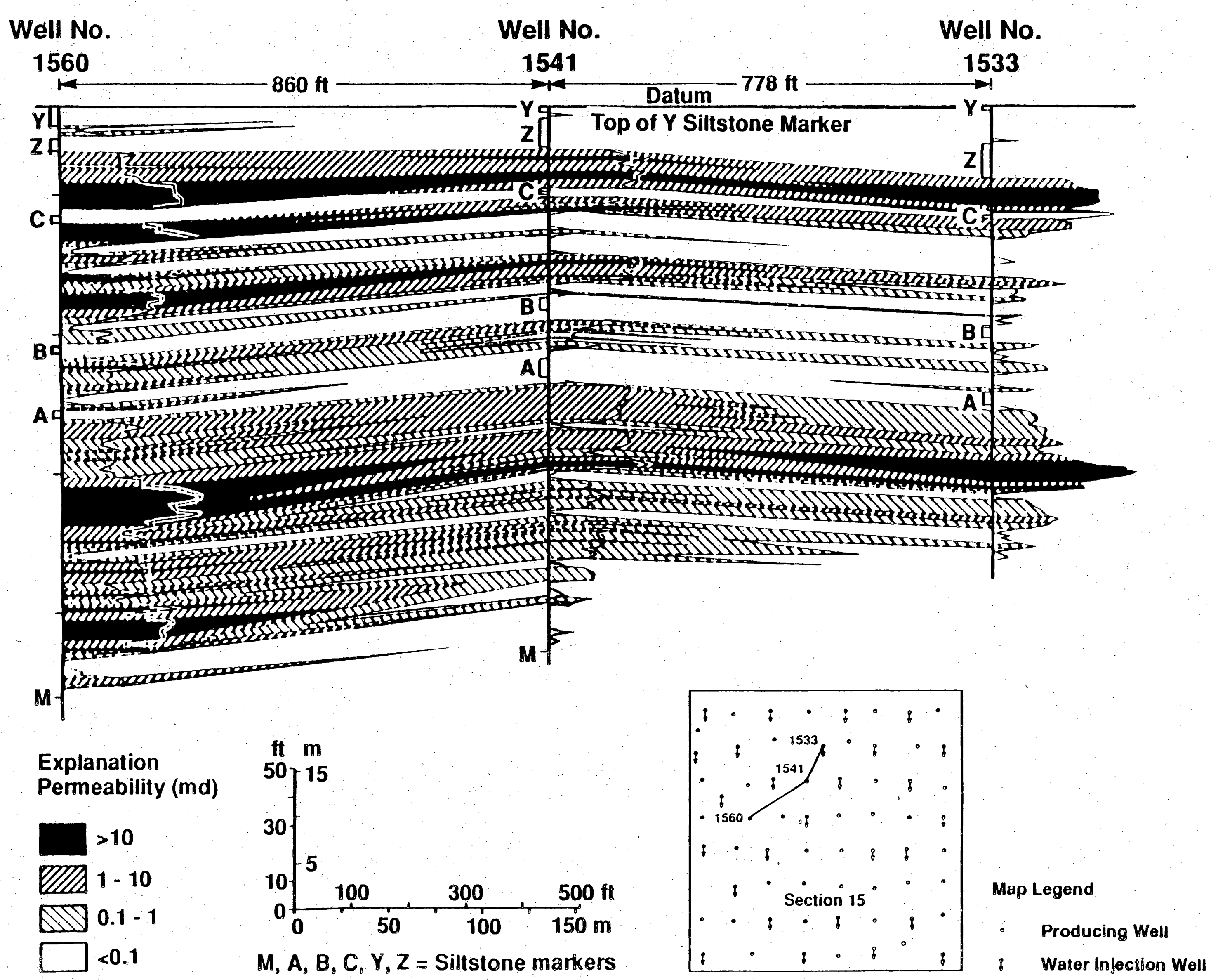
Figure 6

Permeability Cross - Section Parallel to Depositional Dip
Dune Field -- Section 15



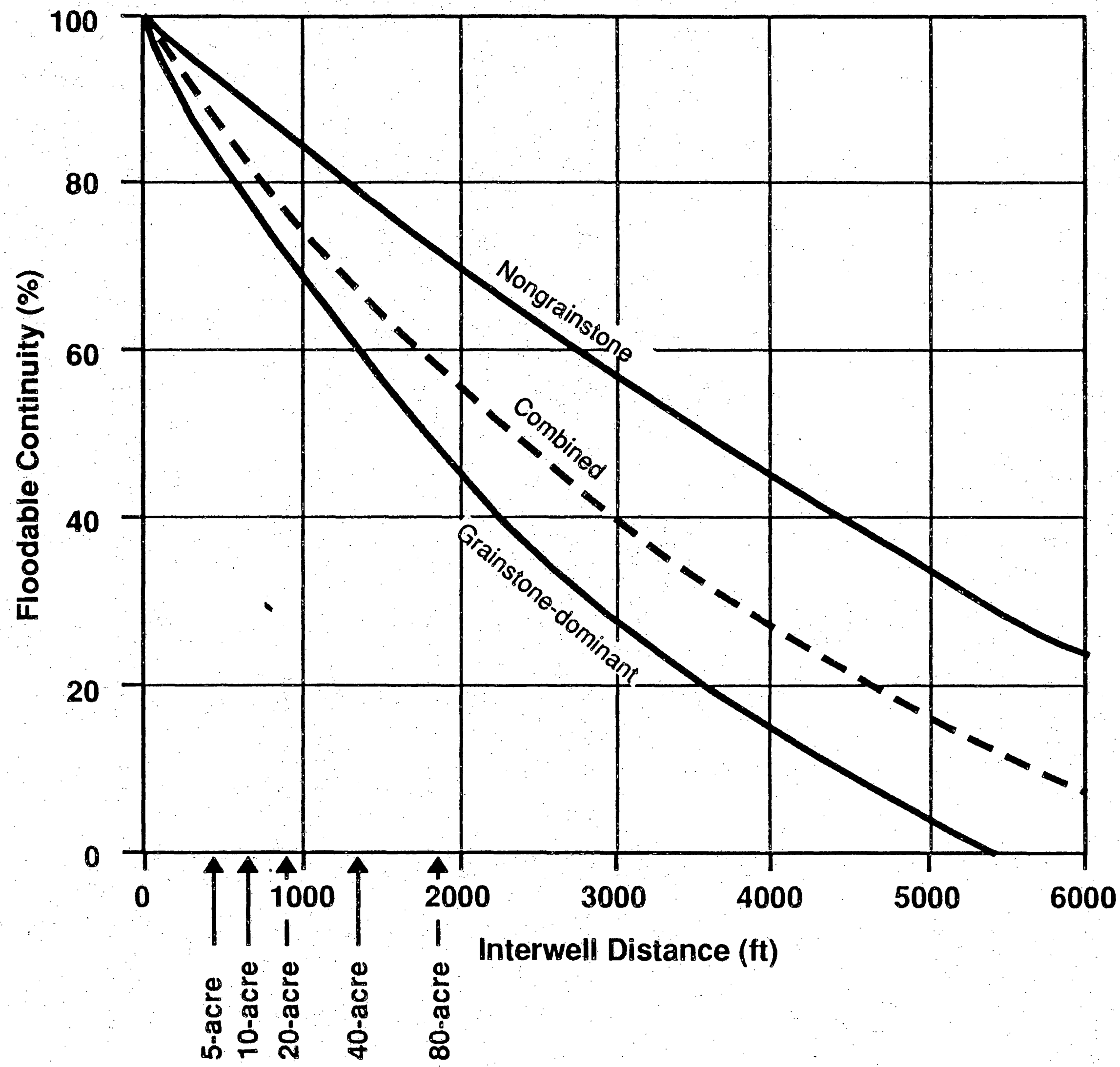
A quantitative method of relating facies pay-continuity to well spacing in Section 15 was developed after Stiles (1976). This method calculates pay continuity by dividing the cross-sectional area of pay zones that are continuous between a well pair by the total cross-sectional area of continuous and noncontinuous pay zones between the well pair. Drainable and floodable pay-continuity functions were established for each facies and for Section 15 as a whole to account for oil recovery by primary solution gas drive and secondary waterflooding of the oil, respectively. The drainable function was developed by combining data from implementation of the Stiles method (1976), production history, and previous pay-continuity work on West Texas carbonate reservoirs by George and Stiles (1978). The floodable pay-continuity function was determined entirely from the use of Section 15 permeability cross sections. Continuous pay between wells was measured as floodable when there was less than two orders of magnitude of contrast laterally in permeability from one well to the other. The area of continuous floodable pay was then divided by the total continuous and noncontinuous pay area between the well pair to establish the percent of floodable pay-continuity at the distance between the wells.

Figure 7 shows the floodable continuity curves for Section 15 as a whole (combined curve), as well as those for the grainstone-dominant and nongrainstone facies. The curves show that the grainstone-dominant facies is more heterogeneous than the Section 15 average and significantly more heterogeneous than the nongrainstone facies. The combined-facies curve represents the continuity relationship corresponding to the blanket infill development of Section 15, while the grainstone-dominant and nongrainstone curves represent the continuity achieved from infill development of these facies individually. Because other facies volumes for fields in the play were not available, the distribution of mobile oil between the grainstone-dominant and nongrainstone facies in the other reservoirs of the play was assumed to be the same as that for Section 15. Although additional facies occur and produce oil in other portions of Dune Field, as well as other fields in the play, it has been qualitatively shown that subtidal grainstones are commonly the predominant producing facies in other Central Basin Platform San Andres/Grayburg reservoirs (Garber and Harris, 1986; Ward and others, 1986). Section 15 facies volumes were assumed for the other fields in the play, then, to the estimate the potential of the play. Further work is

Figure 7

Floodable Continuity Curves
Grainstone-Dominant vs. Nongrainstone

Dune Field -- Section 15



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required to determine a more precise distribution of facies and unrecovered mobile oil for the other reservoirs in the play.

Once established, the pay continuity functions for Section 15 were used to estimate the volume of remaining mobile oil in the reservoir at current spacing. The facies-specific curves indicate that pay-continuity in the grainstone-dominant facies has less drainable and floodable continuity than the nongrainstone at the same well spacing, implying that the grainstone facies contains more remaining mobile oil per equivalent volume of rock and could be targeted for new infill wells. For example, the floodable pay continuity curve for the grainstone dominant facies indicates that an additional 8% of total net pay in this facies can be contacted by drilling from 20-acre well spacing to 10-acre spacing in Section 15. This additional 8% contact corresponds to 470 thousand barrels (MB) of oil recoverable by waterflooding after infill drilling and primary production in the grainstone facies. In contrast, only an additional 100 MB of remaining mobile oil, corresponding to an additional 4% of net pay in the thinner, nongrainstone facies can be recovered through waterflooding after drilling from 20-acre to 10-acre well spacing in Section 15.

Figure 8 and Table 2 present the results of the economic analyses for several infill development programs considered for Section 15. The analyses consider infill development starting at a pattern spacing of 80 acres per production well. Blanket infill projects implemented in an ongoing waterflood, for both a single drilldown (base case) and for selective reservoir-wide infill development, are considered, along with geologically targeted infill development in both an ongoing waterflood and a depleted field. For blanket infill development in an ongoing waterflood, economic recovery of 1.0 MMB is achievable at an oil price of $10 per barrel from infill drilling from 80 to 40 acres per producer. Another one-half reduction in pattern spacing in Section 15 to 20 acres per well is economically feasible at $20 per barrel, where a total of 2.0 MMB are economic to produce. Further blanket infill drilling below 20 acres per well is not economically viable at prices to $30 per barrel.

A strategic geologically targeted infill development program targets the more heterogeneous grainstone-dominant facies, allowing closer development in this facies compared to that possible

Figure 8

Results of the Economic Evaluation of Dune Field Section 15 for Several Different Development Scenarios

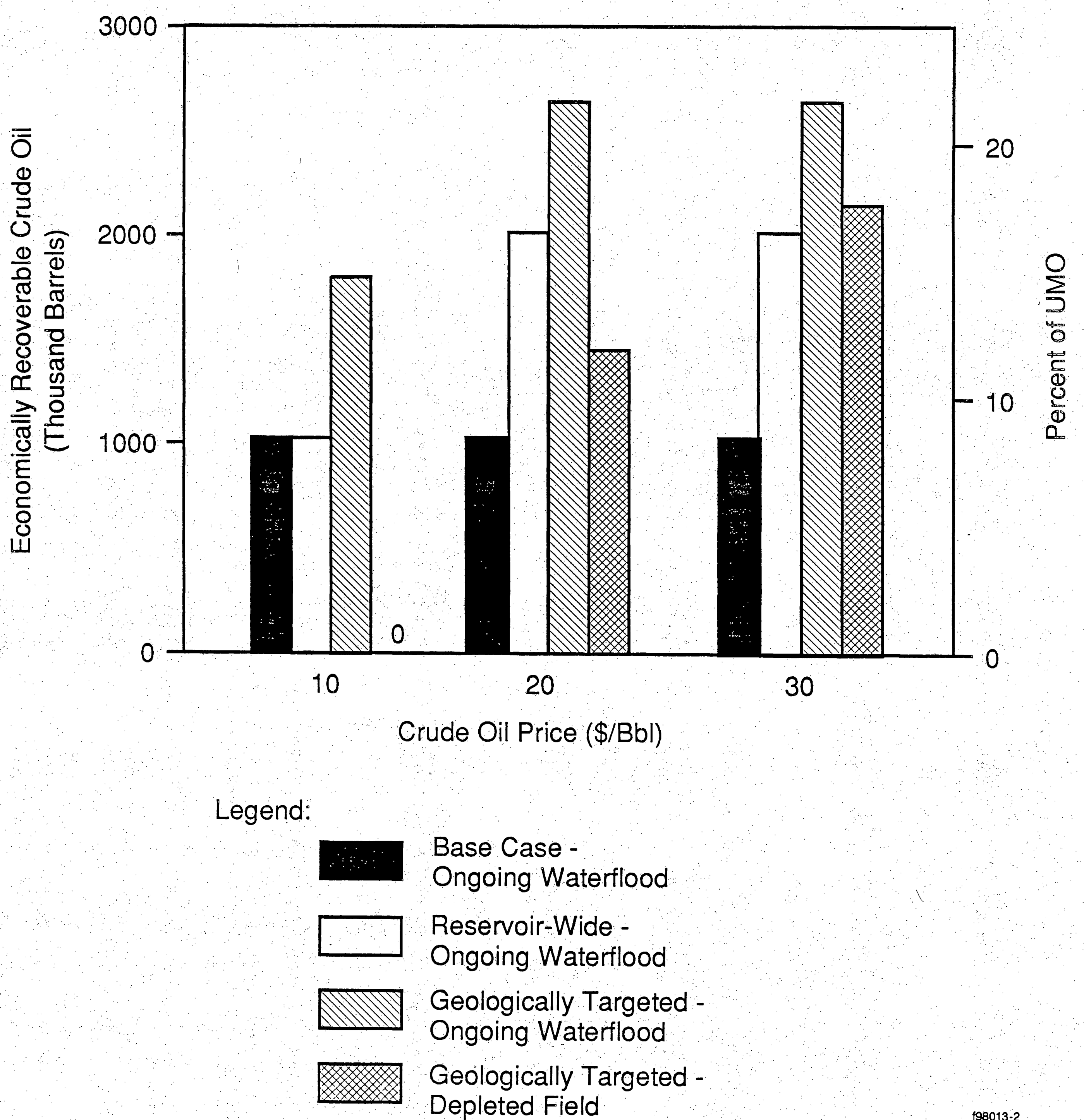

Table 2

Comparison Between Blanket and Targeted
Infill Drilling in Section 15, Dune Field

Crude Oil Price ($/Bbl)	Blanket: Minimum Econ. Spacing (Acres/Well)		Blanket: Econ. Recov. Oil (MMB)	Targeted*: Minimum Econ. Spacing (Acres/Well)		Targeted*: Econ. Recov. Oil (MMB)
	Grainstone	Nongrainstone		Grainstone	Nongrainstone	
Ongoing Waterflood						
$10	40	40	1.0	20	40	1.8
$20	20	20	2.0	10	40	2.6
$30	20	20	2.0	10	40	2.6
After Waterflood						
$10	80	80	0	80	80	0
$20	40	40	0.8	20	40*	1.5
$30	20	20	1.6	10	40	2.1

*Blanket infill development to 40 acres/producer, where economic, was assumed in the targeted development scenario.

throughout the reservoir. Under the targeted infill drilling scenario, it was assumed that blanket development would take place from 80 to 40 acres per producer. This assumes that a single reduction in spacing will take place reservoir-wide before advanced geologic understanding can lead to geologically targeted infill drilling and greater economic recovery.

The economic analyses show that greater UMO recovery can be obtained from targeted infill development over that obtained from blanket development. Table 2 compares the minimum pattern spacing in each facies at which economic development can take place under both a targeted and blanket infill development program. In addition, Table 2 and Figure 8 show the economically recoverable oil for each price and development strategy considered. For example, at an oil price of $10 per barrel, economic infill development in an ongoing waterflood in the grainstone-dominant facies is feasible to 20 acres per producer, compared to development to only 40 acres per well in the nongrainstone facies. (Blanket infill drilling was assumed to 40 acres per producer.) At this price, a total of 1.8 MMB of UMO are economically recoverable from targeted drilling in the grainstone-dominant facies, compared to 1.0 MMB recoverable from blanket development.

To examine the effects of project timing on infill drilling economics, a scenario was considered where the operator waited to begin infill development until the end of waterflood operations, when the section would be economically depleted at current spacing. The comparison of the two development timing scenarios shown in Figure 8 for the advanced targeted infill case shows that delaying project implementation lowers the economic potential at all oil prices and drilling strategies considered. The early implementation of infill drilling results in an increase in reserves and an acceleration in oil recovery, improving project economics. For example, at a price of $10 per barrel, geologically targeted infill development is uneconomic in the depleted section, but 1.8 MMB are economic to produce from targeted development in an ongoing waterflood. Similar results are obtained at higher prices and for other development strategies. This analysis clearly demonstrates the time urgency of applying UMO recovery techniques in mature domestic reservoirs.

When blanket infill drilling to the minimum economic spacing is considered (selective reservoir-wide case), the difference in economic UMO recovery between geologically targeted and blanket infill drilling narrows as prices rise. This narrowing results because as prices increase, a larger fraction of UMO in Section 15 becomes economic to develop by blanket infill drilling. Consequently, a smaller share of the UMO target is available for strategic development. At lower prices, less resource is economic to blanket infill drill, and therefore, the potential for strategic development is greater.

Under blanket development, as prices rise, the return from production in the more heterogeneous (grainstone-dominant) facies is sufficiently high such that the wells in the less heterogeneous (nongrainstone) facies can be economically supported. For this reason, the resource associated with these nongrainstone wells is considered economically recoverable under a blanket infill program. In fact, the less productive wells in the nongrainstone facies would not be economic at the prices considered if evaluated separately. Importantly, the economic viability of wells in the grainstone-dominant facies improves considerably when these wells are no longer supporting the less productive, nongrainstone wells. The wells in the grainstone-dominant facies can economically produce at a considerably lower cost per barrel than an average well, allowing development to closer spacing than possible under blanket development.

In the extrapolation of the results of Section 15 to the other reservoirs in the play, each reservoir was assumed to be represented by the continuity curves for Section 15. Moreover, the reservoir pore volume distribution between the grainstone-dominant and nongrainstone facies was assumed in all reservoirs to be the same as that existing in Section 15. Given this assumption, the UMO target was determined individually for each reservoir in the San Andres/Grayburg Carbonate (South Central Basin Platform) Play, and it was determined that approximately 624 MMB of crude oil represent the uncontacted mobile oil in the play technically recoverable by infill drilling from current spacing in each reservoir to 10 acres per producing well. Reservoir heterogeneity, as controlled by the original depositional system, is the major factor influencing the remaining recoverable mobile oil in the play. However, the prevailing oil prices and the infill development approach are the key factors that determine the economic recovery from the reservoirs in the play.

Under the base case, which assumes the implementation of blanket infill projects in ongoing waterfloods, the following results were obtained for the play:

- At an oil price of $10 per barrel, 165 MMB would be recoverable, representing 6% of the UMO target.
- At a $20 per barrel oil price, 210 MMB are economic to produce, representing 7% of the UMO target.
- At $30 per barrel, 220 MMB are economically recoverable, amounting to 8% of the UMO target.

For selective reservoir-wide infill development, infill drilling continues to the minimum spacing economically justified in each reservoir. This scenario assumes that sufficient geologic information on reservoir heterogeneity is available to assess and to implement the drilling program in each reservoir where it appears feasible and to reduce the risk associated with reservoir-wide infill development to closer spacing. Under this scenario, the potential for the play is as follows:

- At an oil price of $10 per barrel, 285 MMB would be recovered, representing 10% of the UMO target.
- At a $20 per barrel oil price, 465 MMB would be recovered, representing 16% of the UMO target.
- At a price of $30 per barrel, economically recoverable reserves would increase to 535 MMB, 19% of the UMO target.

A program of geologically targeted infill development, based on a detailed, facies-specific characterization of reservoir heterogeneity, could appreciably improve UMO recovery economics at low oil prices. By directing wells toward geologically favorable areas, the potential of targeted infill drilling in the play is estimated as follows:

- At an oil price of $10 per barrel, recovery from targeted infill drilling would be 440 MMB (16% of the UMO target), 155 MMB more than could be recovered under selective reservoir-wide infill development, and 275 MMB more than that recovered from the base case.

- At an oil price of $20 per barrel, 505 MMB of oil (18% of the UMO target) would be economically recoverable, 40 MMB more than that recovered from selective reservoir-wide infill drilling, and 295 MMB more than that recoverable from the base case.

- At $30 per barrel, the recovery potential from targeted drilling would decline slightly (from 535 to 530 MMB), relative to selective reservoir-wide infill development. The recovery potential, however, is 310 MMB greater than that in the base case. In addition, production in the more favorable areas would proceed at a considerably lower cost per barrel than average wells under blanket development at this price.

Even after infill drilling to close spacing, the San Andres/Grayburg Carbonate (South Central Basin Platform) Play has 1,694 MMB of mobile oil that have been or will be contacted but most of which has not been recovered, bypassed by secondary recovery operations. The recovery potential of this bypassed oil was not explicitly evaluated in this study, although a portion of this oil is included in the recoverable estimates. A further portion of this resource would be recoverable from infill development at closer spacing and from improved secondary recovery techniques, such as profile modification and selective zone recompletion.

Frio Barrier-Strandplain Play

The Frio Barrier-Strandplain Play produces oil and associated gas in the Texas Gulf Coast Province from reservoirs characterized by a complex interplay of clastic depositional facies and structural elements. This prolific play is defined geologically by the intersection of the regionally extensive Frio and Vicksburg Fault Zones and sandstones of the Greta-Carancahua barrier-strandplain system of the Oligocene Frio Formation. The play consists of 44 major oil reservoirs, each having produced over 10 MMB of crude oil as of 1981. Collectively, these reservoirs contained original oil in place estimated at 4.2 billion barrels. These reservoirs have produced over 1.8 billion barrels of oil to 1981 (Galloway and others, 1983) with remaining proved reserves of 0.4 billion barrels. Although overall recovery efficiencies in the Frio Barrier-Strandplain Play are relatively high (52%, on average, considering past production plus remaining proved reserves), certain portions of the reservoirs have low recovery efficiencies and are very good candidates for infill development.

The representative reservoir selected for the Frio Barrier-Strandplain Play was the 41-A reservoir in the West Ranch field (Figure 9). The 41-A reservoir is considered to be representative of the other reservoirs in the Frio Barrier-Strandplain Play because it contains all of the predominant barrier-strandplain facies in the play, such as barrier core, tidal inlet, flood-tidal delta, and back-barrier lagoon. Figure 10 exhibits the typical facies components found in the play. Additionally, the values of many key reservoir properties in the 41-A reservoir, such as recovery efficiency, porosity, and residual oil and water saturation, are similar to the average values for the other reservoirs in the play.

Galloway and Cheng (1985) previously mapped the distribution of the three main barrier-island facies in West Ranch field. The 41-A reservoir consists of strike-parallel barrier-core facies with tabular geometries. These barrier-core facies have been eroded in some segments of the reservoir by dip-parallel, tidal-inlet facies that are lenticular in cross section. The tidal-inlet facies comprises about 50% of the reservoir by volume and the barrier-core facies constitutes approximately 31%. Both of these facies grade updip into thin flood-tidal delta and muddy back-barrier lagoonal facies which make up the remaining 19% of the reservoir volume. Although the barrier-core facies is internally homogeneous, the tidal-inlet facies is highly variable in nature and contains large variations in sandstone content and sedimentary structures. Uncontacted compartments in the 41-A reservoir are located in the tidal-inlet facies, as well as in the flood-tidal deltas and washover fans which comprise the seaward side of the back-barrier.

The Stiles (1976) pay-continuity method was initially considered for use in the pay-continuity analysis of the 41-A reservoir. However, this method was not applicable to this reservoir because it was originally developed for reservoirs in which the pay zones occur as thin, discontinuous stringers. In the relatively unstratified 41-A reservoir, the Stiles method yielded values of pay continuity that increased with distance between well pairs, instead of decreasing in accordance with geologically based expectations. Therefore, an alternate method of establishing pay continuity was devised, based on kh (permeability multiplied by pay zone thickness) ratios between adjacent wells.

Figure 9

Location of Frio Barrier-Strandplain Fields, West Ranch Field and 41-A Study Area

(after Galloway and others, 1983; Tyler and others, 1984)

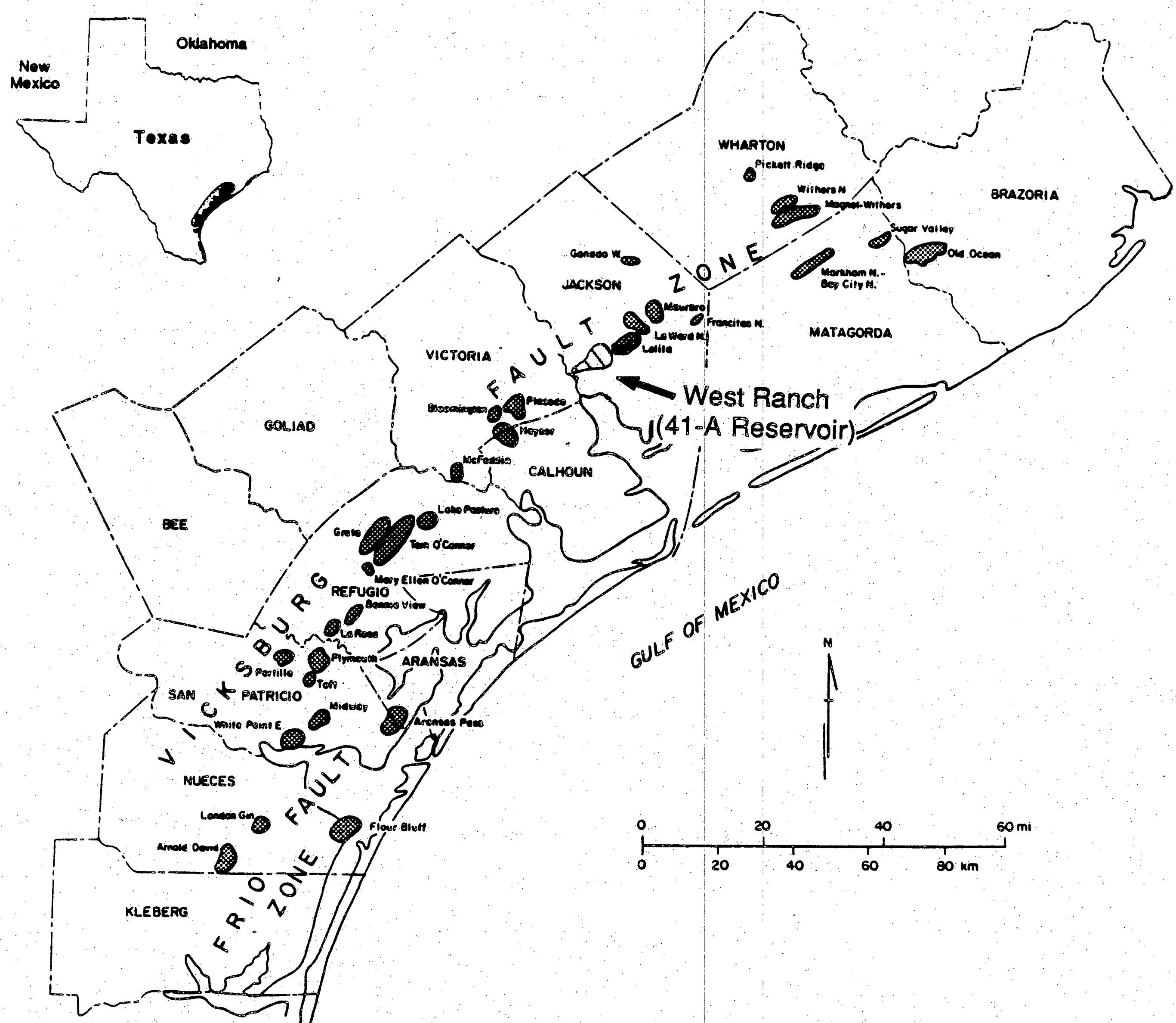

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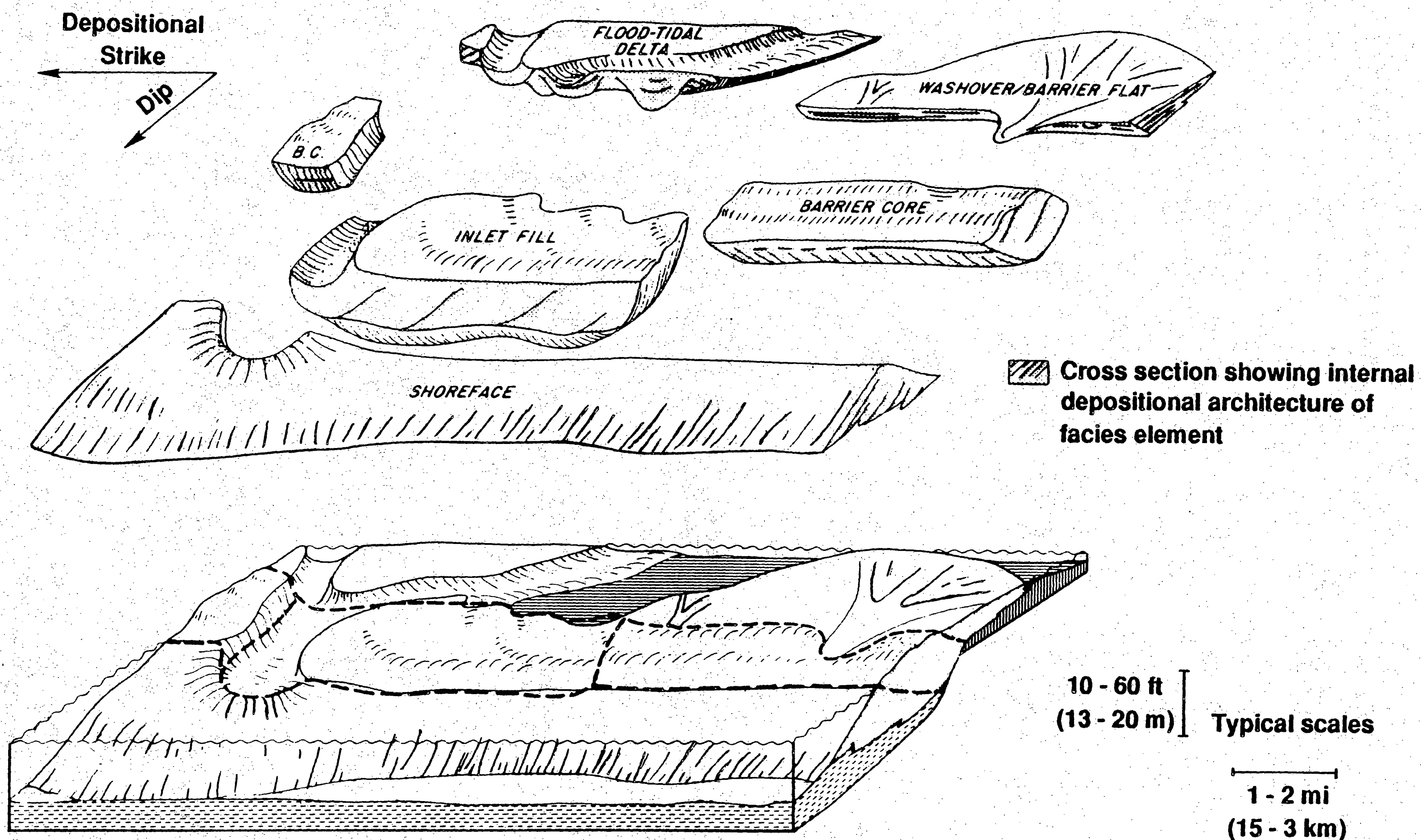
Figure 10

Facies Components in Barrier-Strandplain Sand Bodies

(from Galloway and Cheng, 1985)



Data from 41 wells on five cross sections that intersect all major facies in the 41-A reservoir were used in the pay-continuity analysis. The kh values in each well were extrapolated from a resistivity-permeability relationship between whole-core data and deep-induction resistivity log response as developed by Galloway and Cheng (1985). For adjacent wells on the cross sections, the pay continuity was defined simply as the kh ratio between the wells. To determine pay continuity between two wells separated by large distances, the kh ratios between each intervening well pair were multiplied together. This process resulted in decreasing pay continuity over increasing distance between wells. Individual pay-continuity functions were constructed for each facies in the 41-A reservoir, as well as for the reservoir as a whole. A comparison of the facies-specific and reservoir-wide continuity curves in Figure 11 shows that the back-barrier and tidal-inlet facies are considerably more heterogeneous than the barrier-core facies and the reservoir as a whole. The greater net pay thickness of the tidal-inlet facies combined with its relatively low pay continuity give it the greatest potential for infill development. In addition, other infill opportunities exist along the edge of the back-barrier facies, where tidal-delta and washover-fan sandstones pinch out into lagoonal mudstones on one side and into barrier-core and tidal-inlet deposits on the other. These sites coincide with areas where variations in lateral and vertical permeability are greatest in the reservoir.

The results for the analysis of the 41-A reservoir show that geologically targeted infill development also leads to increased economic recovery over that achieved under blanket development. A comparison of the economic potential of blanket and geologically targeted infill drilling in the 41-A reservoir is shown in Figure 12 and in Table 3. For a single blanket reduction in spacing in the reservoir from 80 to 40 acres per well (the base case), only 13.0 MMB would be economically recoverable at an oil price of $10 per barrel. However, at the same price, 22.5 MMB would be economically recoverable from selective reservoir-wide infill development to a minimum spacing of 20 acres per well in all facies. No additional reserves are added from further reservoir-wide development at oil prices up to $30 per barrel.

At $20 per barrel, 27.0 MMB could be economically recoverable from targeted infill development, 20% more than selective reservoir-wide infill development and 108% more than that

Figure 11

Pay-Continuity Functions in Major Facies and Combined Facies for the 41-A Reservoir, West Ranch Field

(after Galloway and others, 1983; Tyler and others, 1984)

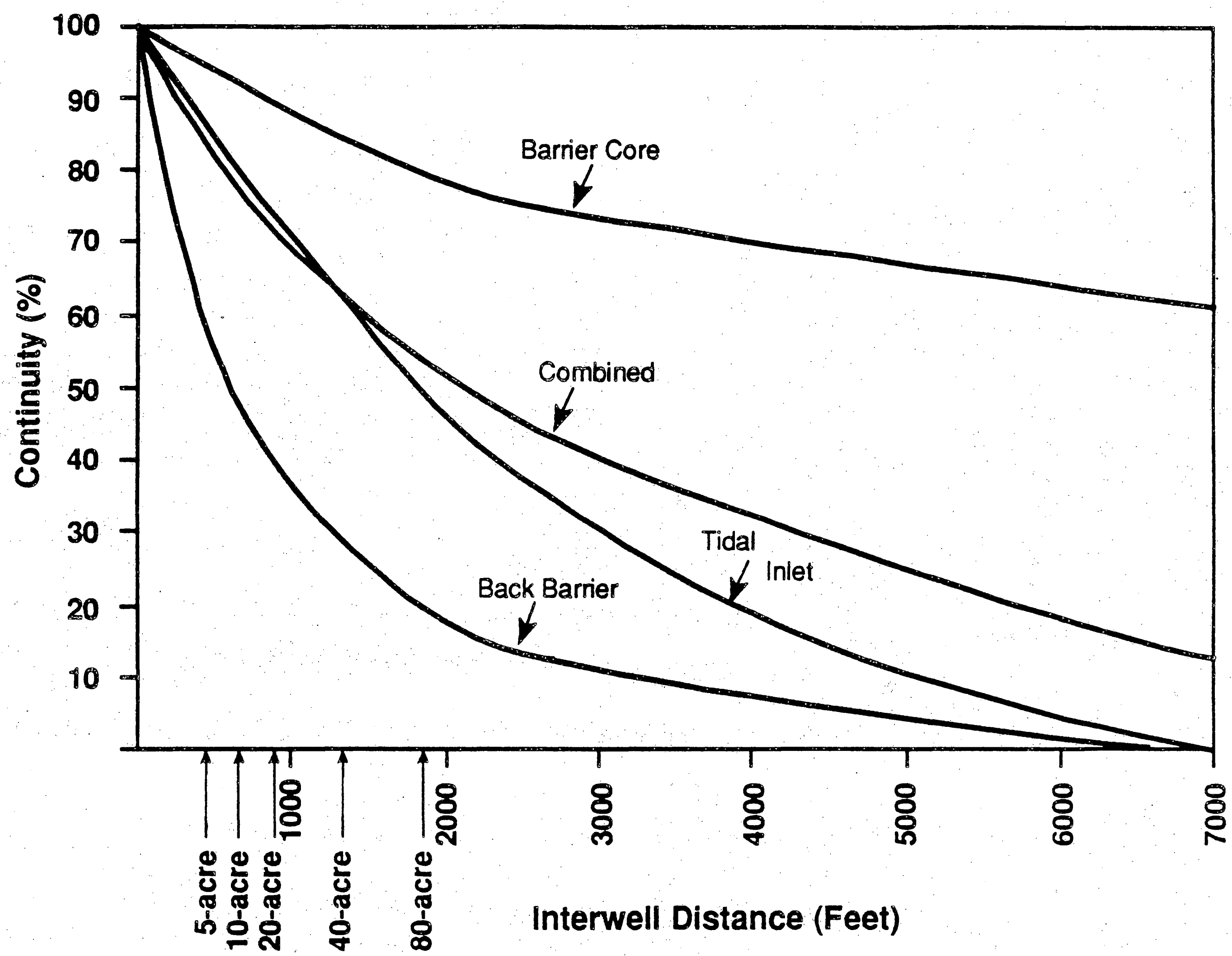


Figure 12

Comparison of the Economic Potential of Blanket and Strategic Infill Drilling in the West Ranch, 41-A Reservoir

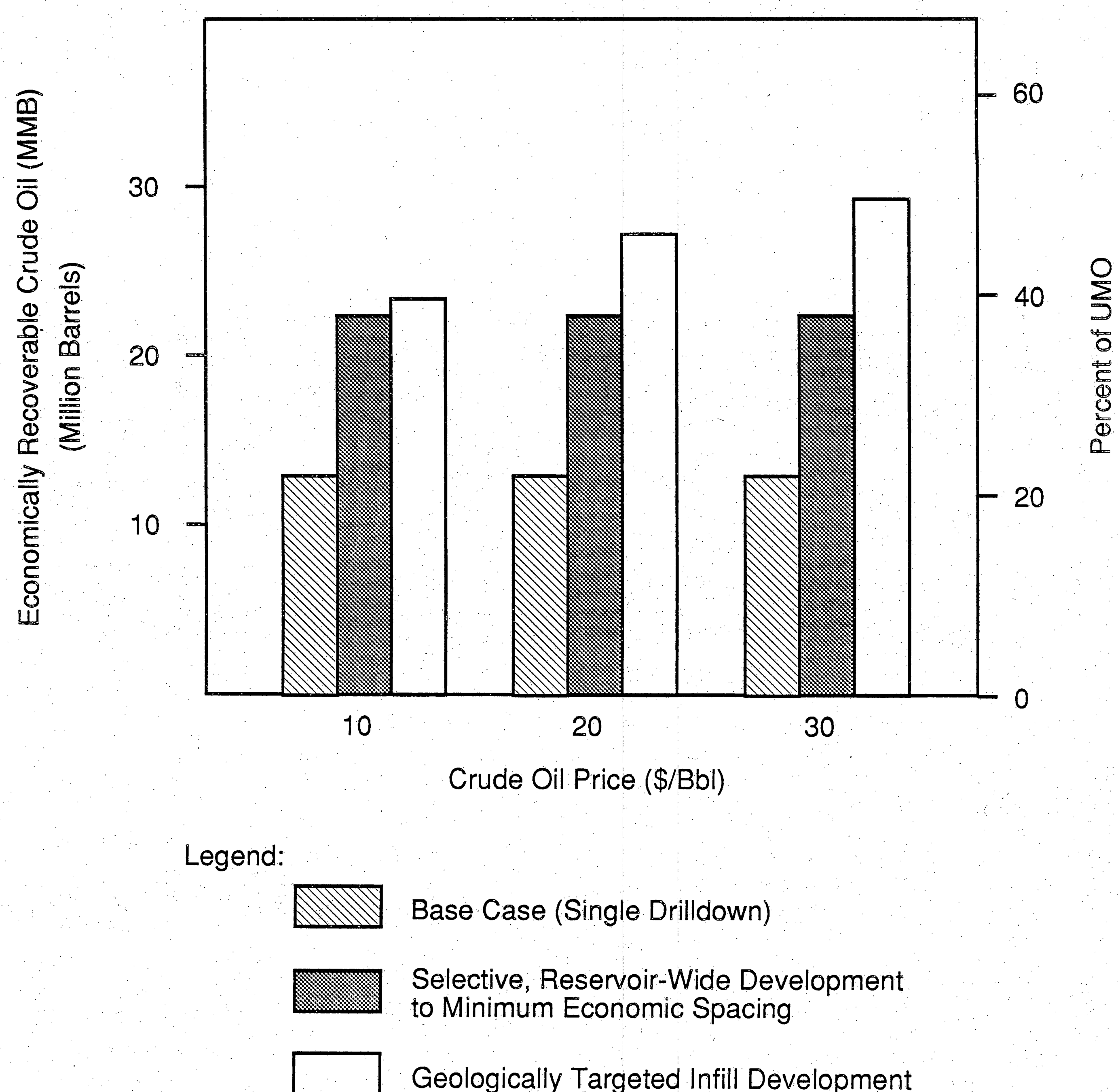


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Table 3

Comparison Between Blanket and Targeted Infill Drilling in the 41-A Reservoir, West Ranch Field

	Blanket		Targeted			
Crude Oil Price ($/Bbl)	Minimum Economic Spacing (Acres/Well)	Economically Recoverable Oil (MMB)	Minimum Economic Spacing (Acres/Well)			Economically Recoverable Oil (MMB)
			TI	BC	BB	
$10	20	22.5	10	40	40	23.4
$20	20	22.5	10	20	20	27.0
$30	20	22.5	10	20	10	29.3

TI = tidal-inlet facies
BC = barrier-core facies
BB = back-barrier facies

from the base case. At $20 per barrel, the tidal-inlet facies could be developed to a pattern spacing of 10 acres per well, while both the back-barrier and barrier-core facies could be developed to only 20 acres per well.

For purposes of extrapolating the results for the representative reservoir (and each facies within the reservoir) to the other reservoirs in the play, each reservoir was assigned a specific volumetric distribution of facies. Each facies is characterized by a unique pay-continuity curve. All of the reservoirs in the play were analyzed in order to determine an estimate of relative facies volume in each. This analysis resulted in six facies volume-distribution types, with each reservoir being assigned to an appropriate type. Reservoirs for which facies-volume information was unknown were assumed to be similar to the West Ranch 41-A reservoir, and were assigned the 41-A facies-volume distribution by default. Other individual reservoir properties, including porosity, initial and residual oil saturation, and formation volume factors, were also used in analyzing the play-wide recovery potential.

Under a program of infill development to 10 acres per producer, the technically recoverable crude oil resource in the Frio Barrier-Strandplain Play is approximately 263 MMB. The economic viability of achieving this potential varies depending on crude oil prices and the development strategy undertaken. Since most of the reservoirs in the play produce from a strong water drive and are already near the end of their project life at existing spacing, only infill development starting at the end of current operations was considered.

Under base case conditions, assuming a single, blanket reduction in spacing of all infill projects in the play, the following results were obtained:

- At an oil price of $10 per barrel, 90 MMB of oil would be economic to produce, representing 10% of the UMO target.
- At prices of $20 per barrel, 120 MMB are economically recoverable, representing 13% of the UMO target.
- At a price of $30 per barrel, 130 MMB are economically recoverable, representing 14% of the UMO target.

Selective reservoir-wide infill development to the minimum pattern spacing economically justified would be based on sufficient geologic information on reservoir-wide heterogeneity to reduce the risk associated with infill drilling programs of this scale. Under this scenario, the following results were obtained:

- At oil prices of $10 per barrel, 115 MMB of oil (representing 13% of the UMO target) would be economically recoverable.
- At an oil price of $20 per barrel, 190 MMB of oil (21% of the UMO target) would be economically recoverable.
- At a price of $30 per barrel, 240 MMB of oil (26% of the UMO target) would be economically recoverable.

A program of geologically directed infill development, based on a significant level of intra-reservoir geologic knowledge could appreciably improve the economic viability of crude oil recovery in the play at low oil prices:

- At an oil price of $10 per barrel, approximately 150 MMB of oil (16% of the UMO target) is recoverable, 35 MMB more than is recoverable from selective, reservoir-wide infill development, and 60 MMB more than that obtained from the base case. The bulk of the low-cost resource would be produced from the tidal-inlet facies.
- At an oil price of $20 per barrel, 215 MMB of oil (24% of the UMO target) would be economically recoverable, 25 MMB of oil over that obtained from selective reservoir-wide infill development, but 95 MMB more than that obtained from the base case.
- At a price of $30 per barrel, 245 MMB of oil (27% of the UMO target) are potentially recoverable. This is only 5 MMB over that obtained from selective, reservoir-wide infill development, but 115 MMB more than that achieved from the base case. However, per barrel costs in the development of heterogeneous, more prolific portions of reservoirs would be substantially less than the average per barrel costs under blanket development.

The difference in recoverable oil from full blanket and strategic infill development to a minimum economic spacing narrows in the Frio Barrier-Strandplain Play in a manner similar to that which would occur in the San Andres/Grayburg Carbonate (South Central Basin Platform) Play. Under geologically targeted development, a large fraction of the total resource recoverable at $30 per barrel is actually recoverable from the tidal-inlet facies at costs below $10 per barrel. The remaining economically recoverable oil at prices of $30 per barrel will come from the relatively thin back-barrier facies and the relatively continuous barrier-core facies. At lower prices, a much smaller portion of the resource is recoverable under blanket development. When higher prices are achieved, more of the reservoir becomes economic for blanket development, and the economically recoverable reserves under this scenario catch up with that obtainable from strategic development.

Finally, in the Frio Barrier-Strandplain Play, only 48 MMB of oil would be considered bypassed, out of a total UMO resource of 910 MMB. The low proportion of bypassed oil occurs because the clastic reservoirs of this play exhibit low vertical heterogeneity, resulting in high vertical sweep efficiencies. The average sweep efficiency is also enhanced by the low oil viscosity and strong natural water drive experienced in most reservoirs in the play. These factors combine to significantly enhance the sweep efficiency of, and resulting recovery by, primary and secondary recovery operations.

Clear Form Platform Carbonate Play

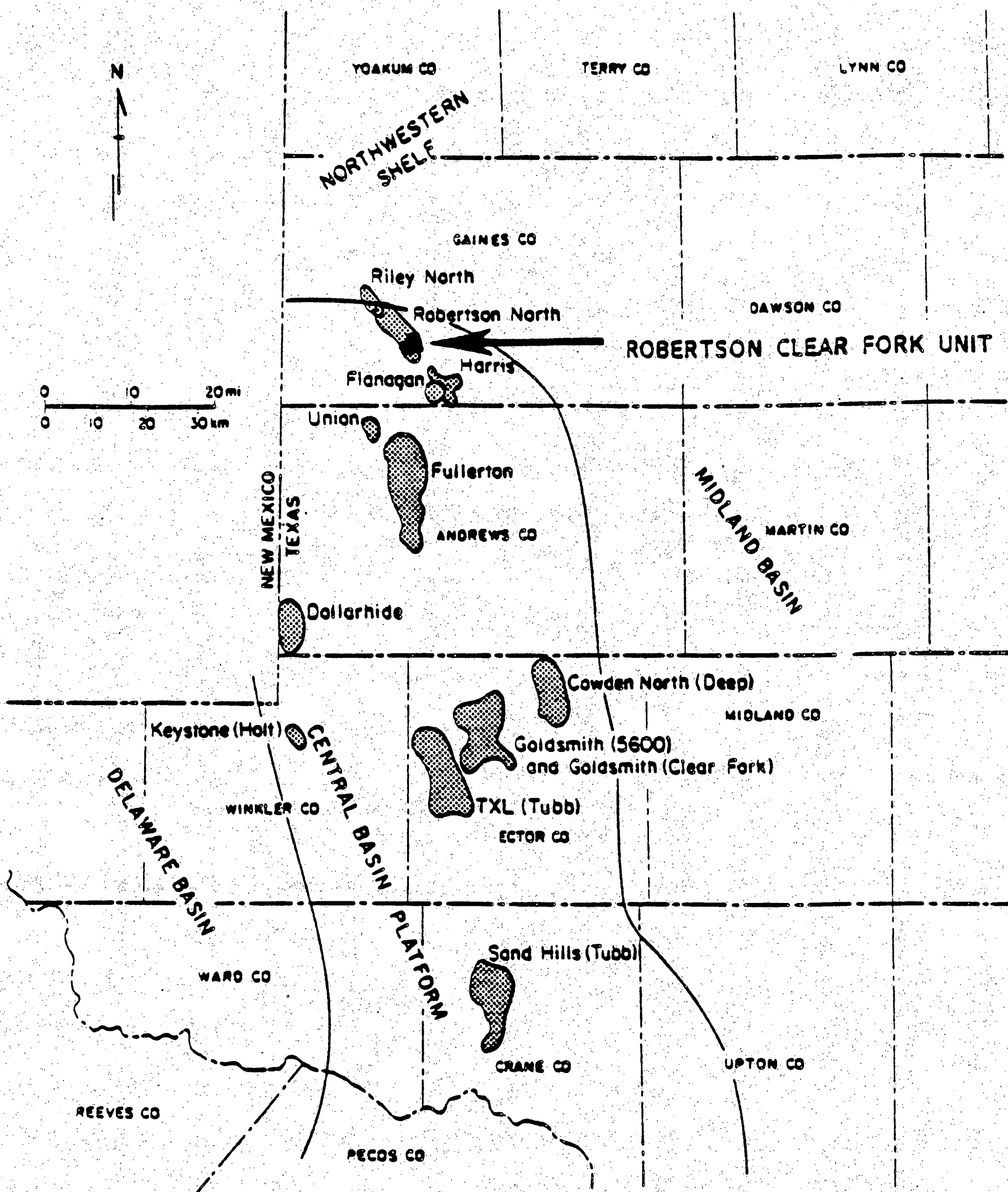
The Clear Fork Platform Carbonate Play, located on the Central Basin Platform of the Permian Basin in West Texas, produces oil and associated gas from heterogeneous interbedded carbonate and clastic reservoirs in the Leonardian Series of Permian age. The play consists of 13 major reservoirs which have each produced over 10 MMB of crude oil as of 1981. Collectively, these reservoirs contained over 4.4 billion barrels of original oil in place and have produced 840 million barrels of oil to 1981 (Galloway and others, 1983). The high heterogeneity in these reservoirs leads to low recovery efficiencies, and therefore, considerable quantities of unrecovered mobile oil. All of these reservoirs have reached primary depletion, and secondary recovery programs are currently underway.

The Robertson Clear Fork Unit in Robertson North field was selected as the representative study area in this play (Figure 13). Having undergone an intensive program of infill drilling, the

Figure 13

Location of the Clear Fork Platform Play and Robertson Clear Fork Unit

(after Galloway and others, 1983)



Robertson Clear Fork Unit served as a useful model for assessing the potential for infill drilling in other fields in the play. Because of insufficient data, however, no facies-specific geological analyses were conducted, and therefore, no facies-specific continuity relationships were established. As a result, only the potential of blanket infill development was assessed for this play. The reservoir-wide drainable and floodable continuity functions used for the analysis of Robertson Clear Fork Unit, developed by Barbe and Schnoebelen (1987), are shown in Figure 14. The Robertson Clear Fork Unit is located in the southern part of the Robertson North field on the northeastern edge of the Central Basin Platform in southwestern Gaines County. Robertson North is one of several fields located within a trend of anticlinal structures developed on the margin of the platform; it occupies the southeast end of a large asymmetrical anticline (Neel, 1957). Many of the reservoir units in the Robertson North field, particularly in the Lower Clear Fork Formation, are shelf dolomites with interbedded siltstone and shale (Phipps, 1969).

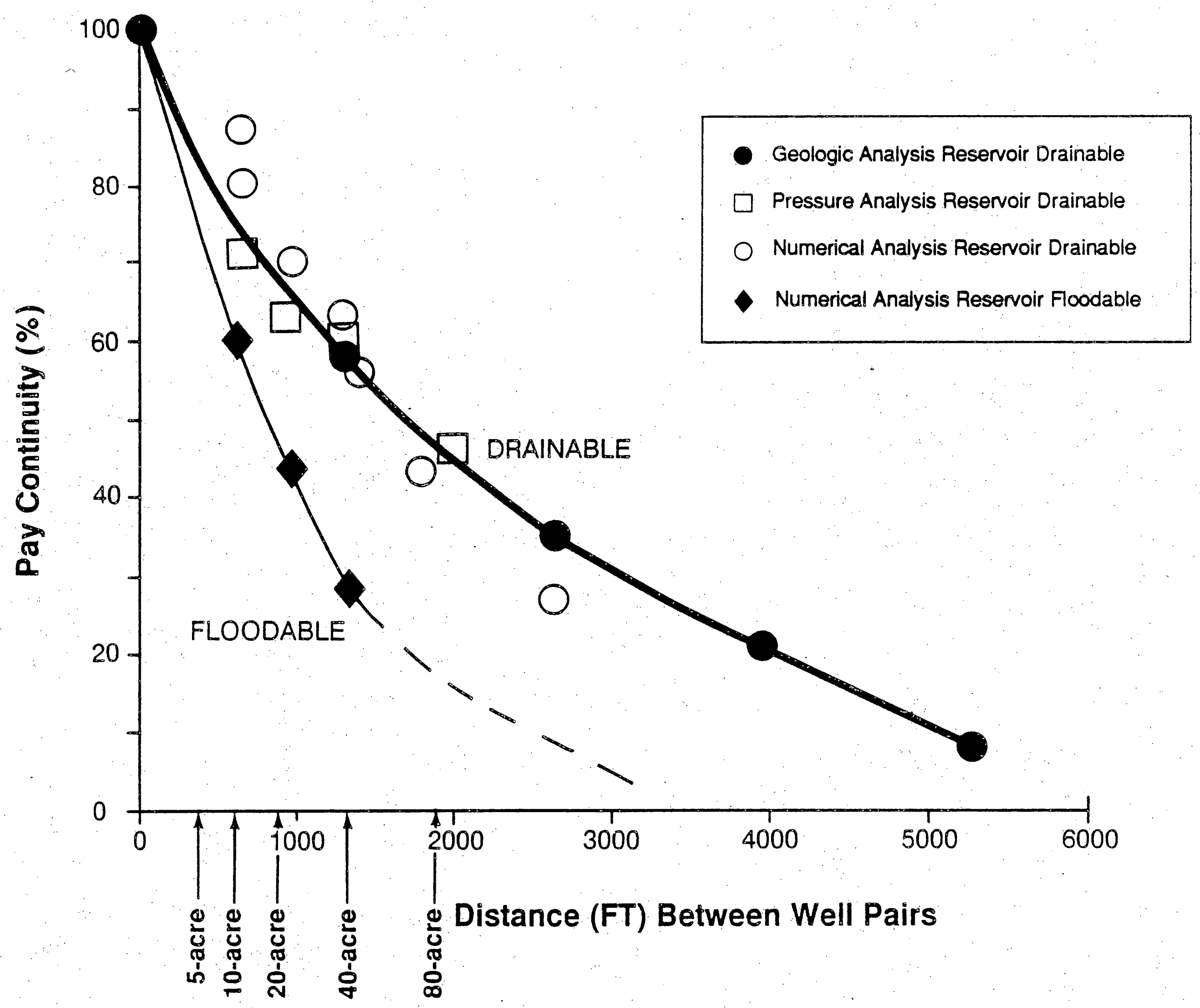
The Clear Fork Platform Carbonate Play is geologically similar to, yet distinct from, the San Andres/Grayburg Carbonate (South Central Basin Platform) Play. The reservoirs of both plays produce crude oil predominantly from carbonate subtidal grainstone bars or shoals (Mazzullo, 1982; Garber and Harris, 1986; Bebout and others, 1987). Although reservoirs of both plays exhibit extreme heterogeneity due to depositional compartmentalization, Clear Fork reservoirs appear to be more complex than San Andres/Grayburg reservoirs as they exhibit up to 70 individual pay stringers, each only 1 to 3 feet thick. The large number of thin pay stringers in the Clear Fork Platform Carbonate Play may be attributed to a smaller scale but greater number of depositional cycles than recognized in San Andres/Grayburg Reservoirs. The slightly greater complexity of the Clear Fork Platform Carbonate Play reservoirs is reflected in the fact that their overall average recovery efficiency of 21% is lower than the average San Andres/Grayburg recovery efficiency of 26% (Galloway and others, 1983; play recovery efficiency average is weighted by the original oil in place of each reservoir).

Post-depositional diagenesis in Clear Fork Platform fields was similar to that in other Permian fields in West Texas such as Dune field (Bebout and others, 1987). Although diagenesis significantly decreased the amount of original porosity, the original depositional environment was

Figure 14

Reservoir (Pay) Continuity Versus Horizontal Distance Between Well Pairs, Robertson Clear Fork Unit

Determined by Geologic, Pressure, and Numerical Analyses
(after Barbe and Schnoebelen, 1987)



a controlling factor in the preservation of some interparticle porosity. Moldic and interparticle porosity are the most common porosity types in the reservoirs of both the Clear Fork Platform Carbonate Play and the San Andres/Grayburg Carbonate Play, but intercrystalline and vugular porosity also occur. Minor occurrences of secondary vugular porosity in the Clear Fork was caused by late-stage dissolution of dolomite and anhydride cement.

Crude oil prices, infill drilling strategies, and the timing of infill development again govern the economics of infill development in the play. This is illustrated by the results of the detailed analysis of the Robertson Clear Fork Unit shown in Figure 15 and summarized below:

- At an oil price of $10 per barrel, approximately 14 MMB would be economic to develop from a single blanket drilldown in the unit from 80 to 40 acres per producer.

- At $10 per barrel, approximately 28 MMB of oil would be economic to produce if selective, reservoir-wide infill development was initiated in an ongoing waterflood at an 80-acre pattern, with economic development feasible to 20 acres per producer.

- If selective reservoir-wide infill development was not initiated until waterflood operations ceased on an 80-acre pattern, only 12.5 MMB of oil would be economic to produce at a $10 per barrel oil price. Economic development would be feasible only to a 40-acre waterflood pattern, representing a single one-half reduction in pattern spacing.

- If oil prices rise to $20 per barrel, no additional incremental oil is economic to produce from an ongoing waterflood in the unit. That is, 28 MMB would be recoverable at this price under selective reservoir-wide development, the same volume that was economic at $10 per barrel.

- If the selective reservoir-wide infill project was initiated after waterflood operations had ceased at 80 acres, only 25.2 MMB are economically recoverable at $20 per barrel, with economic development feasible to 20 acres per producer.

Under a program of selective, reservoir-wide infill development from current spacing to 10 acres per well in ongoing waterfloods in reservoirs in the play, the technical recovery potential in the Clear Fork Platform Carbonate Play is 308 MMB of crude oil. The potential economic UMO recovery in the play is approximately 95 MMB of oil (7% of the UMO target) at an oil price of $10 per barrel under the base case, corresponding to the base case single reduction in spacing in all reservoirs (most reservoirs in the play are at a current spacing of 40 acres per well or less). Approximately 170 MMB of oil (13% of the UMO target) are recoverable under the base case at oil prices of $20 per barrel. At a $30 per barrel oil price, 210 MMB of oil (16% of the UMO target) become economic to produce from selective reservoir-wide infill development to the minimum spacing economically justified, while 170 MMB would be economic in the play under base case conditions.

The Clear Fork Platform Carbonate Play has an estimated 282 MMB of mobile oil that are currently contacted, but most of which is bypassed by current operations. Most of an additional 156 MMB of mobile oil would be contacted, but bypassed, under a blanket infill drilling program to 10 acres per producer. The economic recovery potential of this remaining bypassed oil, a total of 438 MMB, would be the target for improved secondary recovery techniques.

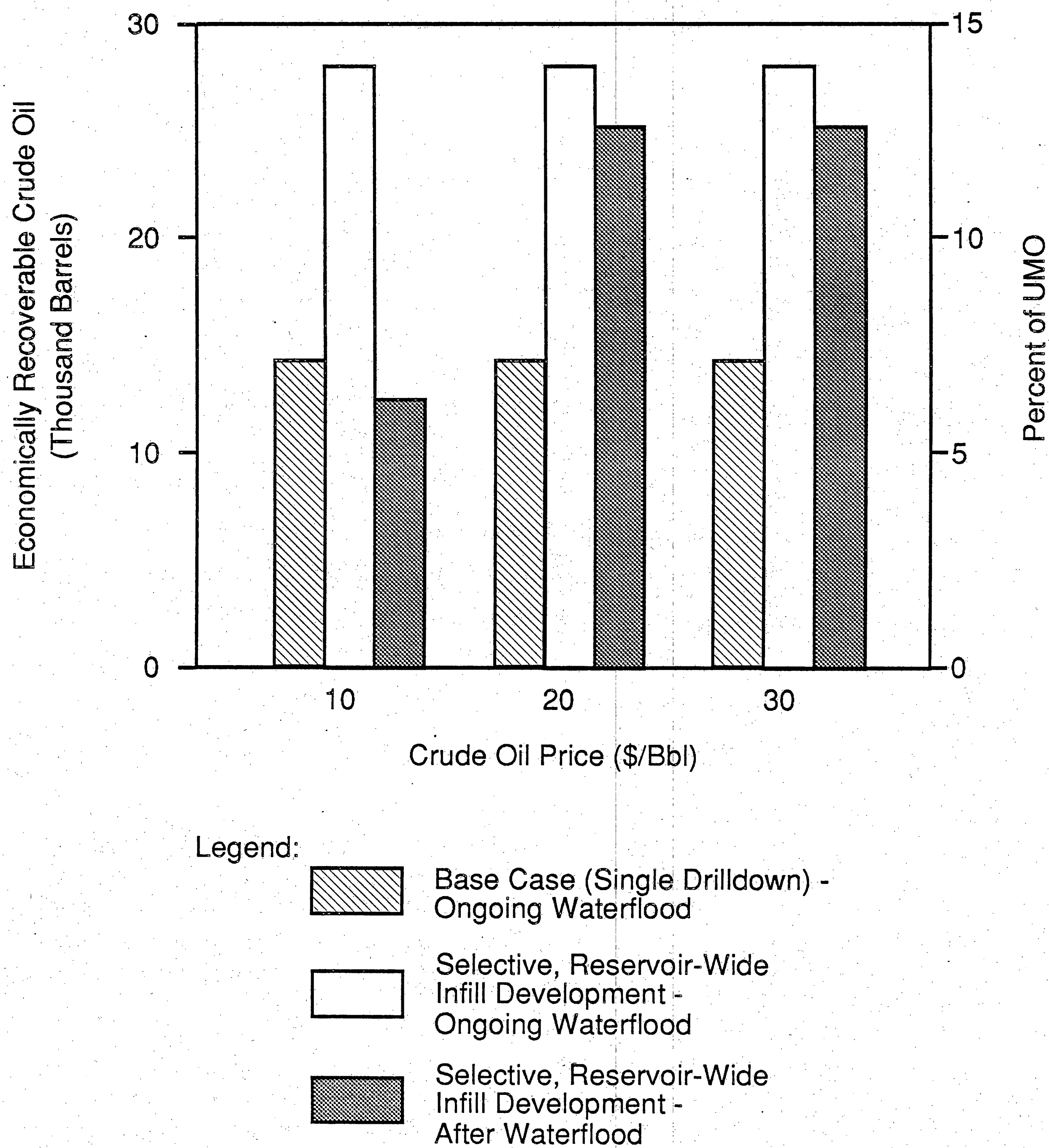
SUMMARY OF THE THREE-STATE REGIONAL ANALYSIS

SUMMARY OF METHODS

Nearly 500 reservoirs containing almost 112 billion barrels of the original oil resource, over one-half of the total resource in Texas, Oklahoma, and New Mexico (and nearly one-quarter of the total domestic resource), were evaluated in this analysis. UMO potential was analyzed for the three states using the expanded and upgraded TORIS system originally developed by the National

Figure 15

Effect of Project Timing on the Economics of Blanket Infill Development in the Robertson Clear Fork Unit



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Petroleum Council (NPC) in their 1984 assessment of enhanced oil recovery (NPC, 1984). In 1988, DOE expanded the capabilities of TORIS to include the evaluation of the UMO resource. This expansion included the development of a series of analytical models used in the TORIS system and an upgrade of the data base to include more detailed geologic information in Texas, Oklahoma, and New Mexico.

While TORIS was developed to evaluate the enhanced oil recovery of immobile oil, the system structure also proved to be well-suited for analyzing UMO recovery potential. TORIS utilizes detailed engineering evaluation techniques, considering data for individual reservoirs to predict recovery, operating costs, required investments and, ultimately, project economics. The system evaluates investment and other costs based on geographic location, depth, and operating conditions of the reservoir and can vary these costs along with the engineering design and the oil price being assessed. Critically important to the UMO recovery analysis is the ability of TORIS to evaluate individual reservoir performance based on distinct rock and fluid properties. Another integral aspect of TORIS is its ability to model various economic and technological conditions, a flexibility which allowed UMO recovery evaluations to be conducted over a range of real oil prices (from $12 to $36 per barrel) and under two technological scenarios, current and advanced.

The current technology scenario evaluated the incremental recovery that would result from a systematic UMO recovery program that utilized current production techniques. Three recovery processes currently used for improving mobile oil displacement were evaluated: infill drilling, permeability modification treatments, and polymer-augmented waterflooding. This analysis was undertaken assuming two levels of geologic understanding and using two classes of polymers. The first level, corresponding to a base case technology scenario, reflected limited geologic understanding of reservoir heterogeneity and the technical shortcomings of currently available polymers used in the field. The second level, corresponding to the advanced technology scenario, reflected the impact of a significantly improved understanding of reservoir heterogeneity and improvements in advanced waterflooding techniques that increase the applicability and productivity of these processes. In the advanced case, it was also assumed that improved polymers would be available, increasing the maximum temperature and salinity at which advanced waterflooding processes can be applied in selected reservoirs.

Potential incremental recovery from infill drilling was estimated from the increased sweep efficiency of similar reservoirs already operating at closer well spacing. Continuity curves that relate reservoir areal sweep to well spacing were derived for various geologically classified reservoir types. These curves were used to calculate the increase in reservoir contact that would result from a given decrease in well spacing. This incremental reservoir contact was then entered into a predictive model to determine the additional waterflood recovery associated with the given decrease in well spacing. Costs were calculated based on the number of new wells required to be drilled and operated in order to achieve the reduced spacing level.

To ensure analytical consistency, the continuity curves derived for the study were used as the basis of both the current (blanket infill drilling) and advanced technology (geologically targeted infill drilling and advanced secondary recovery) evaluations. The advanced geologic interpretation assumption inherent in the advanced technology evaluation was incorporated by dividing each reservoir into two segments -- a more heterogeneous segment and a less heterogeneous segment -- as previously displayed in Figure 3. In the base case, infill drilling potential was estimated reservoir-wide under the assumption that sufficient wells were drilled to reduce the entire reservoir spacing to one-half its current level, with each well encountering the "average" continuity for that spacing. In addition, further reservoir-wide infill development was considered to the minimum pattern spacing economically justified at a specified price, assuming the availability of sufficient geologic information to allow operators to justify the risk of such intensive blanket infill programs. In the advanced case, each reservoir segment was analyzed independently, and drilling in either segment could continue down to five acres, or one-eighth of current spacing, the maximum decrease in well spacing allowed in this evaluation.

Each reservoir was individually analyzed to determine the recovery processes that would be economically viable either in the entire reservoir or in individual reservoir segments. The analytical system then assigned one of these processes to each reservoir or reservoir segment by determining which process generated the largest incremental oil recovery.

At each technology level, two separate analyses were conducted. The first analysis evaluated incremental recovery when only one of the three recovery processes considered was assigned to each reservoir or reservoir segment. The second analysis was structured to reflect the economic viability of selectively combining recovery processes. Since combining infill drilling with polymer flooding or permeability contrast reduction further improves sweep efficiencies, the analysis was conducted to examine the impact that these selective combinations had on incremental mobile oil recovery.

DISCUSSION OF RESULTS

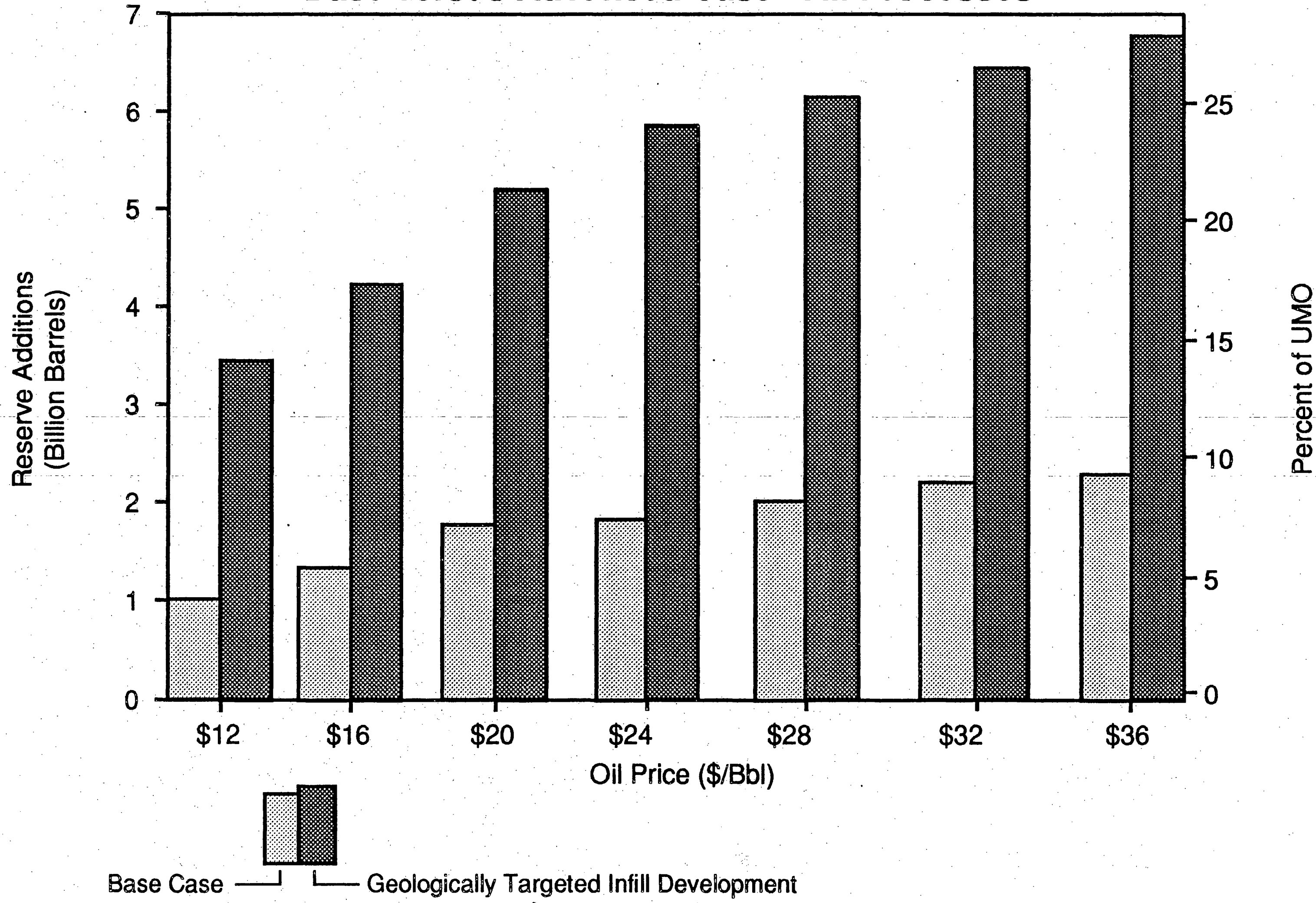
The results of the three-state study indicate that current UMO recovery techniques are economically viable at low oil prices and could recover over one billion barrels of the resource analyzed at $12 per barrel, as displayed in Figure 16. This assumes base case conditions, or a single, one-half reduction in pattern spacing for all reservoirs which are economic to develop by blanket infill drilling, and includes recovery from infill development and conventional advanced secondary recovery processes. Recovery would increase to nearly 1.4 billion barrels and 1.8 billion barrels at $16 per barrel and $20 per barrel, respectively, for the base case. Recovery is less sensitive to further oil price escalation, growing to 2.1 billion barrels at $28 per barrel and 2.3 billion barrels at $36 per barrel, the highest oil price analyzed.

Advanced technology substantially increases UMO recovery potential. As Figure 16 also shows, recovery from advanced techniques could practically triple recovery from the base case, leading to production totals between 3.5 billion (at $12 per barrel) and 6.8 billion barrels (at $36 per barrel). The upper end of this range represents recovery of over 28% of the UMO resource estimated to reside in the analyzed reservoirs.

Figure 16

Mobile Oil Recovery Potential From Analyzed Reservoirs in Three States Texas, Oklahoma, and New Mexico

Base versus Advanced Case - All Processes



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In this analysis, infill drilling was determined to be the single most effective process for the potential recovery of UMO, accounting for between 70% and 90% of the total recovery from the analyzed reservoirs. Figure 17 shows the recovery potential from only infill drilling in the three states for three levels of infill development -- base case; selective, reservoir-wide infill development to a minimum pattern spacing economically justified (maximum of three drilldowns); and geologically targeted infill development to a minimum economic spacing. As stated previously, base case technology could result in 0.6 billion barrels of economically recoverable oil at $12 per barrel, 1.3 billion barrels at $20 per barrel, and 1.8 billion barrels at $32 per barrel. This scenario assumes that operators would be unwilling to assume the risk of further blanket development (i.e., more than one drilldown), without the acquisition of more detailed geologic information on reservoir heterogeneity. However, if operators acquired sufficient geologic information on their reservoirs to reduce the risks associated with blanket infill drilling to very close spacings, then 2.3 billion barrels could be economically recoverable from selective reservoir-wide infill development at $12 per barrel, 4.0 billion barrels could be recoverable at $20 per barrel, and 5.1 billion barrels could be recoverable at an oil price of $32 per barrel.

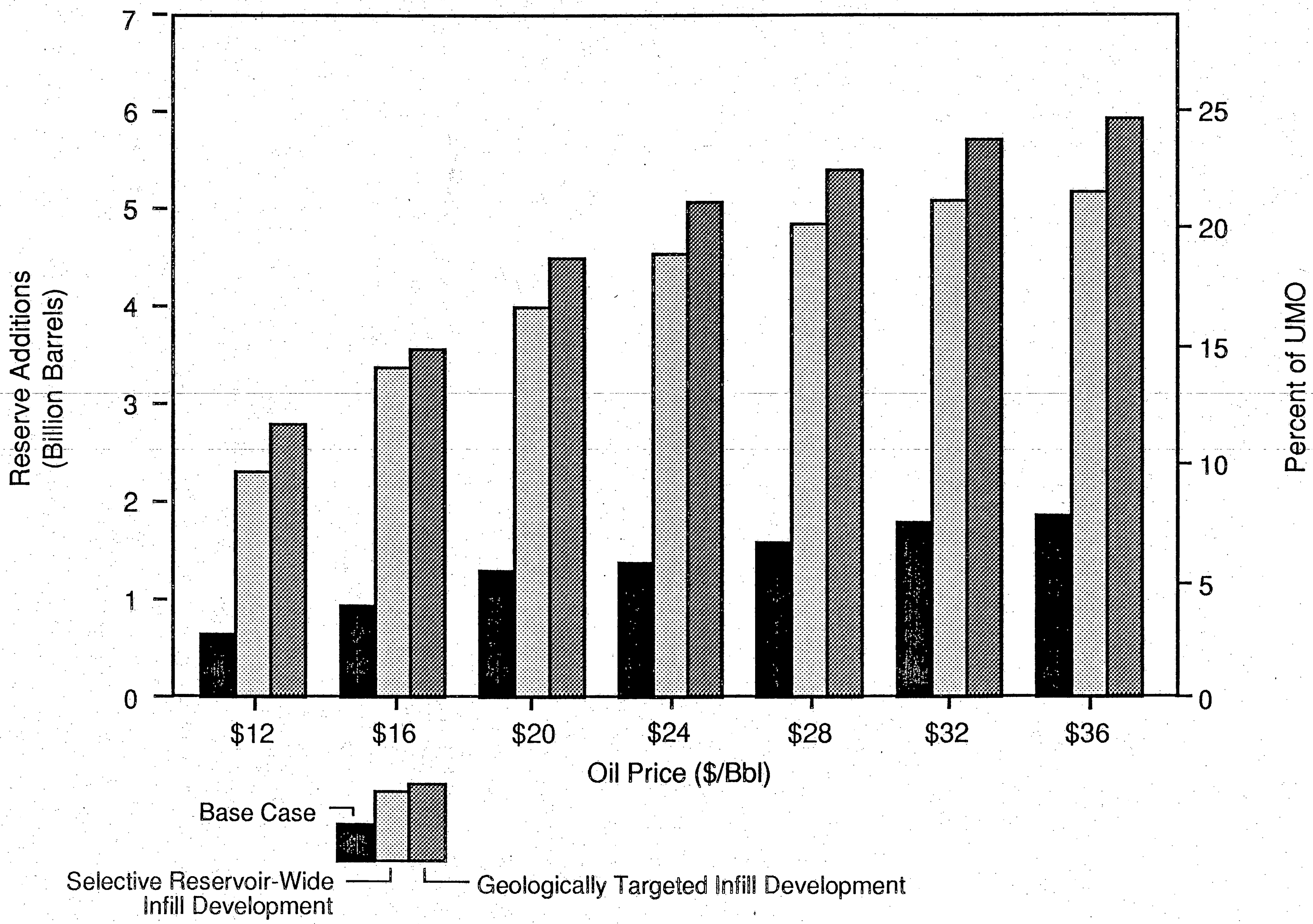
Geologically targeted infill drilling could be between three and four times more productive than base case development. Under geologically targeted development, 2.8 billion barrels could be economically recoverable at a $12 per barrel oil price, 4.5 billion barrels could be recoverable at $20 per barrel, and 5.7 billion barrels could be economically recoverable at a price of $32 per barrel.

Advanced secondary recovery using polymer flooding and profile modification treatments would be less prolific than infill drilling but could result in over 300 million additional barrels of UMO recovery in the three states. Polymer flooding improves the mobility ratio of oil to water, which increases sweep efficiency, while profile modification increases the sweep efficiency of water floods, increasing oil recovery from zones of lower permeability. The most effective application of these processes is in combination with infill drilling. These advanced methods of waterflooding decrease water production in mature projects, reduce operating costs, improve cashflow, extend the project's economic life, and increase recovery. The overall recovery attributable to these

Figure 17

Recovery Potential of Infill Drilling from Analyzed Reservoirs in Three States Texas, Oklahoma, and New Mexico

Base, Three-Drilldown, and Strategic Scenarios



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techniques, alone or in selected combination with infill drilling, could total 400 to 600 MMB of oil, regardless of the oil price or level of technology. Although this volume is small when compared with the recovery potential from infill drilling alone, these relatively low cost techniques have unique applications and represent the only economic alternative for UMO recovery in many reservoirs analyzed.

Table 4 summarizes the results of the three-state study. The nearly 500 reservoirs evaluated originally contained 112 billion barrels of oil. After conventional primary and secondary production is complete, almost 25 billion barrels of mobile oil resource will remain unrecovered in these reservoirs. This oil represents the UMO target for the recovery processes analyzed in this study. An oil price of $12 per barrel, 640 MMB could be recovered in the base case. Given the additional recovery possible from polymer flooding and profile modification, as well as selective combinations of these advanced waterflooding processes with blanket infill drilling, recovery could increase to 1.0 billion barrels, about 4% of the target resource. An increase in oil prices to $20 per barrel could nearly double the recovery potential, with 1.3 billion barrels possible from infill drilling alone and nearly 1.8 billion barrels possible from the application of combined processes.

Advanced technology could dramatically increase UMO recovery potential, even at lower oil prices. At an oil price of $12 per barrel, geologically targeted infill drilling alone could recover nearly 2.8 billion barrels of UMO, over 11% of the total target resource evaluated. Combined processes in the geologically targeted case are projected to produce nearly 3.5 billion barrels at this price, around 14% of the target oil. With higher oil prices of $20 per barrel, these recoveries could increase to over 4.5 billion barrels from strategic drilling and over 5.2 billion barrels from combined processes, 18% to 21% of the analyzed UMO target, respectively.

Selective reservoir-wide infill development in each reservoir could also increase recovery over that from the base case, assuming operators have sufficient geologic information to justify the risk of intensive blanket infill development of selected reservoirs. This information would identify those reservoirs with the greatest infill potential and would allow for the further development of specific reservoirs showing promise. However, the increase in recovery is not as great as that

<u>Table 4</u>

Summary of Unrecovered Mobile Oil Recovery Potential from Analyzed Reservoirs in Three States --
<u>Texas, Oklahoma, and New Mexico</u>

(All Crude Oil Values in Millions of Barrels)

Original Oil in Place	111,700	
Original Mobile Oil in Place	63,200	
Estimated Ultimate Recovery by Current Means	38,700	
Target Oil	24,500	
Economic Recovery at $12/Bbl		
Base Case	641	(3%)*
Selective, Reservoir-Wide Infill	2,305	(9%)
Geologically Targeted Infill	2,794	(11%)
Current Technology with Combined Processes	1,042	(4%)
Advanced Technology with Combined Processes	3,462	(14%)
Economic Recovery at $20/Bbl		
Base Case	1,290	(5%)
Selective, Reservoir-Wide Infill	3,997	(16%)
Geologically Targeted Infill	4,504	(18%)
Current Technology with Combined Processes	1,779	(7%)
Advanced Technology with Combined Processes	5,205	(21%)

*Percentages represent the fraction of the UMO target oil economically recoverable at that price and level of development.

obtained from geologically targeted infill development and the application of advanced secondary recovery processes, since it lacks facies-specific delineation and characterization.

COMPARISON BETWEEN THE RESERVOIR/PLAY AND THREE-STATE STUDIES

Both the reservoir/play studies and the three-state analysis show that a significant portion of the UMO resource could be economically recoverable at low-to-moderate oil prices. Furthermore, both studies show that at low oil prices, geologically targeted infill development could result in the recovery of considerably more oil than that achieved from blanket development.

For the two plays where strategic infill development was considered, the results show that at an oil price of $10 per barrel, approximately 16% of the UMO target is potentially economically recoverable from geologically targeted infill drilling, two to three times the oil recoverable from the base case (Table 1). At this price, targeted intra-reservoir development could recover 30 to 50% more than selective reservoir-wide infill development to the minimum spacing economically justifiable in each reservoir. At an oil price of $20 per barrel, geologically and targeted strategic development could recover 18 to 24% of the UMO target in the San Andres/Greyburg and Frio Barrier-Strandplain Plays, respectively, over 150% more than that recoverable from the base case and 10 to 15% more than that recovered from selective reservoir-wide infill development.

In the three-state study, geologically targeted infill development also results in substantially more recoverable oil at low-to-moderate prices than that achieved from blanket development. At an oil price of $12 per barrel, geologically targeted infill development could recover 11% of the UMO target. At this price, recovery could increase to 14% of the UMO target when advanced secondary recovery processes are combined with targeted infill drilling. This recovery is five times that resulting from the base case and 20 to 50% more than that recovered from selective reservoir-wide infill development (Table 4). At $20 per barrel, targeted infill development recovers 18 to 21% of the UMO target (depending on whether or not advanced secondary recovery processes are also considered), three to four times that recovered from the base case and 15 to 30% more than that recovered from selective reservoir-wide development.

A comparison of the results for the individual play analyses and the three-state study for infill drilling only is presented in Table 5. In the two relevant plays, targeted-infill development could result in 150 to 300% more oil than blanket infill drilling at oil prices of $10 to $20 per barrel, when compared to the base case. In the three-state study, targeted development could recover 300 to 500% more oil than resulted from the base case for the same range in prices. Thus, the difference in potential recovery between advanced geologically targeted and blanket infill drilling in the three-state study is roughly twice that obtained in the detailed play analyses. The difference between blanket and targeted infill development in the play studies pertains to only the further targeted development of the major reservoirs established initially as making up the play (Galloway and others, 1983). In the three-state study, on the other hand, at least part of the difference between blanket and geologically targeted infill development is due to the fact that more UMO resource is considered for the geologically targeted case. Additional reservoirs in the regional study become economic under the more efficient, geologically targeted development case. These reservoirs are not economic under blanket development at the same price. This addition of reservoirs results in a related increase in reserves. On average, over the price range considered, about 50% of the incremental reserve additions between blanket and geologically targeted development is the result of the further development of reservoirs that were economic to blanket infill drill at the same or lower prices, and 50% is attributable to drilling in reservoirs which were uneconomic to develop without geologically targeted infill drilling. If the addition of new reservoirs in the three-state study is not considered, the incremental recovery from targeted infill drilling over that from blanket development is similar in the three-state regional analysis and two reservoir/play studies in which geologically targeted infill drilling was analyzed.

In comparing the results for the reservoir/play studies and the three-state study, shown in Table 5 for all prices and development strategies considered, the portion of the UMO recovered was higher in the plays than in the three states as a whole. This results because the individual plays selected for detailed analysis exhibited high heterogeneity and, thus, better-than-average infill potential. In the three-state study, on the other hand, a wide variety of reservoirs was represented and included reservoirs with various levels of reservoir heterogeneity. Subsequently, both lower and higher cost infill development candidates were represented and analyzed.

Table 5

Comparison of Results for the Individual Play Analysis and the Three State Study for Infill Drilling Only*

(All Values are in Millions of Barrels)

	Total of Three Plays		Total of Three States	
Original Oil in Place	19,095		111,700	
Original Mobile Oil in Place	10,571		63,200	
Estimated Ultimate Recovery by Conventional Means	5,513		38,700	
UMO Target	5,058	[3,737]**	24,500	
Economically Recoverable at $10/Bbl				
Base Case	350	(7%)	641	(3%)
Selective Reservoir-Wide	495	(10%)	2,305	(9%)
Geologically Targeted	595	(16%)**	2,794	(11%)
Economically Recoverable at $20/Bbl				
Base Case	500	(10%)	1,290	(5%)
Selective Reservoir-Wide	825	(16%)	3,997	(16%)
Geologically Targeted	810	(22%)**	4,504	(18%)

*Percentages represent the fraction of the UMO target oil economically recoverable at that price and level of development.

**Totals are for only the two plays where the strategic infill development potential was evaluated.

Finally, the gap between geologically targeted and selective reservoir-wide infill development tended to decrease as prices increased in the play and the three-state analysis. As stated previously in the presentation of the play analyses results, as prices rise, a larger portion of the target resource becomes economic for blanket development, precluding substantial incremental increases in recovery from further geologically targeted development.

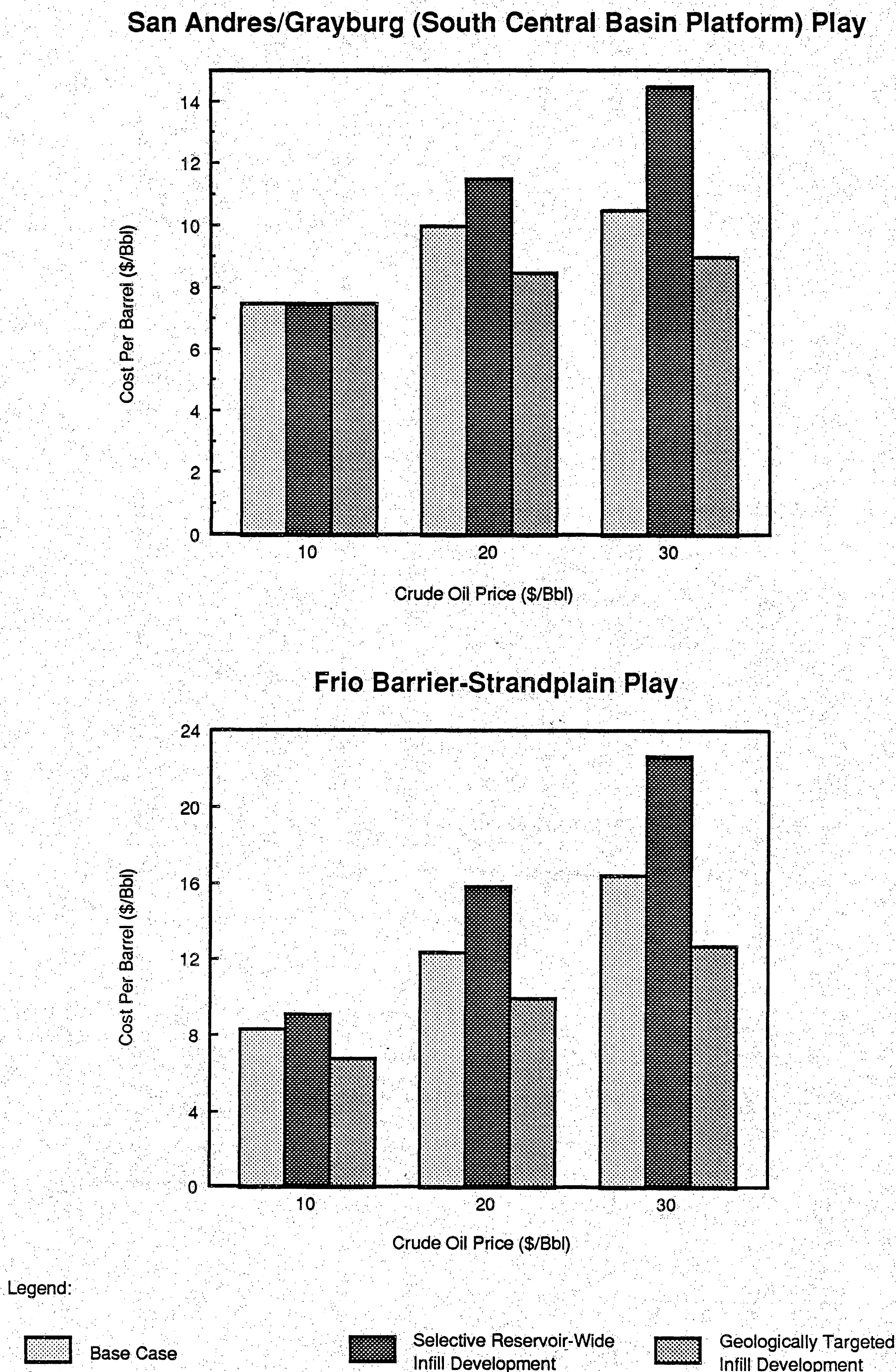
An important economic consideration, however, is that given a fixed UMO resource, geologically targeted infill development will result in lower costs per incremental barrel recovered and, therefore, greater return on investment for operators. Substantially lower costs will result even where the incremental recovery of geologically targeted development over selective reservoir-wide development is small, since under targeted infill drilling, development focuses on the most promising portions of the reservoir.

This is shown in Figure 18 for the San Andres/Grayburg Carbonate (South Central Basin Platform) and Frio Barrier-Strandplain Plays. The total cost per barrel of oil recovered from infill development is displayed for three oil prices and the three dulling scenarios considered. These costs include all development and operating costs and tax obligations. When comparing the results in Figure 18 to the reserve additions results shown in Figure 4, the analyses show that the reserves added from targeted infill development are obtained at equivalent or lower costs compared to reserves added from blanket development. At low oil prices near $10/Bbl, where the development costs per barrel are roughly equivalent, significantly more reserves are added from targeted development. At higher oil prices near $30/Bbl, on the other hand, where reserve additions from infill development are similar, the costs per barrel for targeted infill development are considerably lower.

Similarly, in the three-state study, an analysis was structured to evaluate the effects that geologically targeted wells would have on investment and operating costs in a common set of reservoirs under similar development assumptions. First, the base case scenario estimated the costs of a single blanket drilldown in each reservoir analyzed. Second, the evaluation was extended to

Figure 18

Cost* Per Barrel Comparison for Two Texas Oil Plays



* Investment cost, operating cost, taxes, royalties, and 10% return on investment.

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estimate the change in project economics given highly targeted drilling only in reservoirs determined to be economic in the base case. Therefore, this comparison applies to only the more economically attractive reservoirs. Nonetheless, given a change from blanket to targeted drilling techniques, investment per barrel of oil recovered and total operating spending (investment plus operating costs) per barrel of oil recovered decrease with a reduction in the number of wells required to efficiently develop each reservoir. This method allows for direct comparison of the costs associated with blanket and targeted drilling in the same reservoirs. The results of this analysis are displayed in Figure 19. At an oil price of $12/Bbl, investment costs under the base case total $3.43/Bbl of oil recovered (F-A). Under a targeted drilling approach that limits the number of wells and maximizes recovery per well, this cost declines to $2.87/Bbl, a 17% decrease. Comparable results are also realized at an oil price of $24/Bbl, with investment costs declining from $6.54/Bbl the base case to $5.41/Bbl for geologically targeted wells. At the highest two oil prices considered ($32 and $36/Bbl), the required investments per barrel for the base case are $8.34/Bbl and $8.85/Bbl; under targeted drilling these requirements fall to $6.95/Bbl and $7.46/Bbl, respectively.

The base case requires operator spending per barrel of $5.45/Bbl at the lowest oil price evaluated (F-B). This increases with oil prices to $10.17/Bbl at the oil price of $24/Bbl and to over $13.50/Bbl at $36/Bbl, the highest oil price considered. Under targeted drilling, incremental spending is significantly lower in the reservoirs evaluated. At the $12/Bbl oil price, operator costs decline 14% to $4.70/Bbl. Similar reductions occur across the remainder of the oil prices considered. These costs do not reflect additional operator costs for royalties, taxes, and return on capital which, if included, would sum to the oil prices recognized in the field.

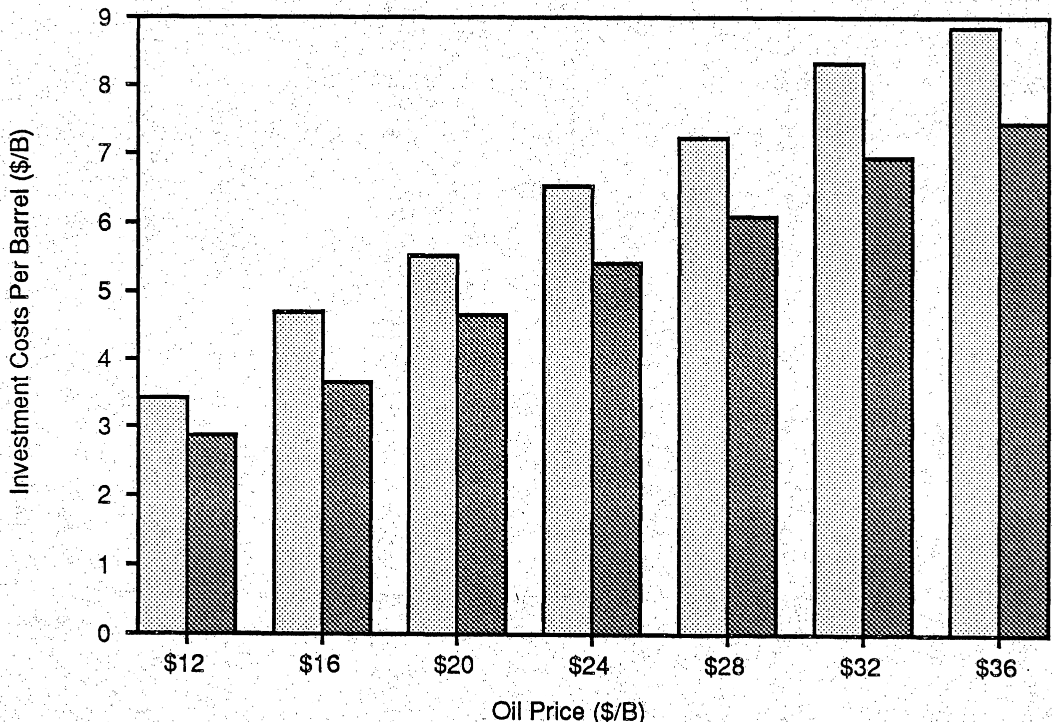
Therefore, as demonstrated in both sets of analyses, depending on prevailing oil prices and a firm's development strategy, geologically targeted infill development can result in increased production (improved cash flow) or lower costs (improved project profitability). In many cases, targeted infill development achieves both.

Figure 19

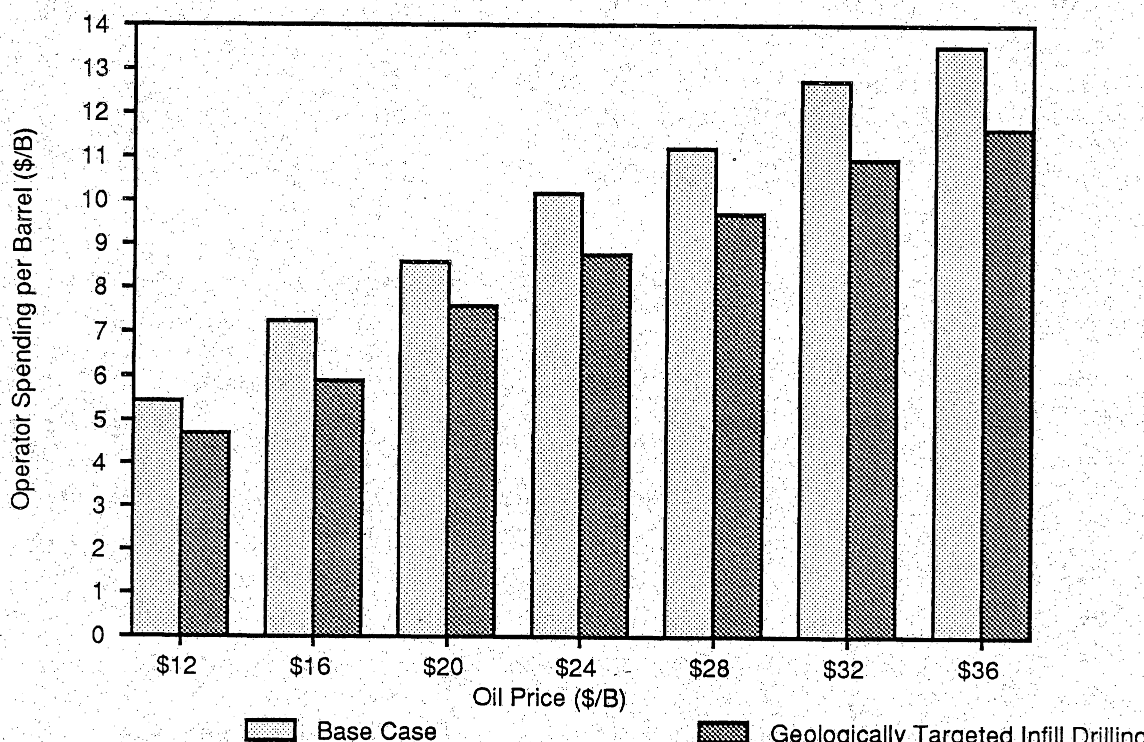
Impact on Project Costs

Blanket versus Targeted Infill Drilling (in Reservoirs Found Economic in the Blanket Case)

A. Investment Costs Per Barrel of Incremental Recovery



B. Operator Spending* Per Barrel of Incremental Recovery



CONCLUSIONS AND DIRECTIONS FOR FUTURE RESEARCH

The recovery of UMO holds great promise for economic development of U.S. resources at the low oil prices expected in the foreseeable future. Moreover, even though significant potential exists with the modest extension of current development practices, even greater recovery can be achieved with the development and application of increased knowledge of reservoir heterogeneities. Classification and quantification of reservoir architecture and flow paths will make it possible to accurately locate and describe UMO in a reservoir, thus allowing the development of techniques that improve reservoir contact and waterflood sweep efficiencies. These techniques include the strategic placement of infill wells, expanding effective floodable reservoir volumes, reducing the effects of high contrasts in permeability among reservoir strata, and improving mobility control in waterfloods. Taken together, these improvements in geoscientific reservoir description and recovery technologies could stimulate enough new production to potentially replace current proved reserves. However, the timely development of improved technologies is essential if the resource is to be exploited. The resource potential shrinks significantly if the techniques are not applied before the end of current operations, a date quickly approaching in many reservoirs.

This series of studies has examined the critically important fundamental hypothesis that improved geological understanding of reservoir heterogeneity can lead to the cost-effective exploitation of the UMO resource. These studies have not tested this hypothesis; rather, they have assumed it to be true and proceeded by evaluating whether its impact on future U.S. production is large enough to warrant further investigation. The results of these studies clearly argue that such further investigations are warranted:

- First, further investigations should test the validity of the fundamental research hypotheses:
  - Increased geologic and engineering understanding of reservoir heterogeneities will improve recovery from selective infill drilling and advanced secondary recovery techniques, reduce the volume of bypassed oil, and improve EOR recovery (the "producibility" hypothesis).

- Increased understanding of heterogeneity in a particular reservoir in a play can be applied (a) to other reservoirs in that play, and (b) to reservoirs in other plays of the same depositional type (the "similarity" hypotheses).

- Second, if the fundamental hypotheses are found to be sound, research should exploit the resultant implications, directly leading to increased U.S. reserves.

Because the "similarity" hypotheses are critical to cost-effective evaluation of the first hypothesis, they must be tested first, since their validity will direct the future and more thorough testing of the fundamental "producibility" hypothesis.

As the testing of these hypotheses proceeds, considerable conceptual development will be required. As with any new research area, the fundamental concepts must be defined and re-defined until they have operational utility. In the present series of studies, for example, all the numerous geologic features that contribute to the true heterogeneity of actual reservoirs have been abstracted into the concept of "continuity" because, in the methodology used, this relatively simple concept exhibits desirable analytical tractability and permits evaluation of the implications of the hypotheses, the present objective. Perhaps the similarity hypotheses will be found to mean that facies or other reservoir units having common depositions will, in fact, have common continuity functions. However, more highly differentiated descriptions of heterogeneity and more complex mathematical representations may be required to fully test these hypotheses. The more parsimonious the concept in terms of measurement, description, and quantification, the broader its application. The needed conceptual development should seek the simplest formulations that are consistent with practical application. Researchers should be prepared to find the similarities in terms of relative proportions among facies, functional relationships between depositional events and resulting reservoir units, or stochastic relationships. Further, reservoir modelers will need to develop techniques for simulating fluid flow in reservoirs described in such terms. Moreover, it is possible that the hypotheses may prove true for certain classes of depositional systems and not for others or may prove true in different ways for different classes. Such findings would, themselves, be critical for appropriately applying the hypotheses.

Testing of the similarity hypotheses can proceed at three levels simultaneously: modern environments, outcrops, and in actual reservoirs. The first two of these are relatively more rapid and less costly to implement than the third and could be used for a number of depositional classes relatively early in the hypothesis testing phase. Testing in actual reservoirs, however, is the only definitive test of either the similarity or the producibility hypotheses. Early tests of the hypotheses could use the three reservoir/play assessments of the present series as baselines for comparison with other reservoirs in the same plays and other plays of similar deposition.

The testing and later exploitation of these hypotheses should proceed in the depositional classes of reservoirs with the greatest incremental gain attributable to the improved geologic understanding and more efficient recovery technologies. Additional criteria, especially the urgency defined by the time of expected abandonment of existing wells, could also be applied. In either case, careful selection of classes, plays, and reservoirs will require detailed analysis. Expansion of the TORIS system to all of the major oil-producing states will permit judicious preliminary selections; updating TORIS based on the results of the research will maintain and enhance the capability for subsequent selections. The ability of TORIS to support these selections would also be improved by thorough peer review of the present methodology and by more complete reconciliation of the methods used in TORIS and the three reservoir/play level studies. This would also define the ways in which field-level research results could be directly incorporated into TORIS.

While the discussion to this point has focused on recovery of mobile oil, the same steps are equally critical in making the recovery of the immobile resource predictably and economically viable. More enhanced oil recovery projects have failed due to an inadequate understanding of the reservoir than from any other cause. Thus, the selection of reservoirs should consider the potential incremental economic recovery of remaining oil due to R&D based on both mobile and immobile oil, separately and in combination. Additional TORIS development will also be needed to properly treat the synergies between recovery of unrecovered mobile oil, especially by infill drilling and enhanced recovery of immobile oil.

Focusing a significant portion of oil research towards specific, well-selected plays could have profound implications for future directions of the federal petroleum research program. Appendix A to this report develops some of the important strategic implications in greater detail.

In conclusion, the present series of studies has found that the UMO resource is large, with significant portions amenable to R&D that will make it economically recoverable at expected future oil prices. Further research and development is clearly warranted. Because much of the heterogeneity research required to make UMO producible is also required to make EOR cost-effective, the entire known domestic oil resource is the proper research target.

The future for producing the unrecovered mobile oil resource appears bright; in synergy with enhanced oil recovery, even brighter. The challenge is clear for a strategically focused, coordinated research program, integrating the contributions of the many relevant disciplines to make a major contribution to the nation's well-being.

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APPENDIX A

UNDERSTANDING RESERVOIR HETEROGENEITY: THE KEY TO A FEDERAL RESEARCH PROGRAM FOR THE EFFECTIVE DEVELOPMENT OF U.S. OIL AND GAS RESOURCES

Goal and Objectives

- Goal:

  Maximize technical and economic producibility of the known U.S. oil and gas resource. This will reduce the nation's trade and fiscal deficits, improve its energy security, and enhance its environmental quality.

- Program Objectives:

  - Increase the understanding and quantification of reservoir heterogeneity, architecture, and flow paths sufficiently to:

    -- Define classes of reservoirs by assembling "plays" with common depositional and diagenetic histories and grouping such plays into classes based on geologic similarity.

    -- Determine the location and condition of remaining oil and gas in "specimen" reservoirs that are representative of the nation's most significant classes of plays.

    -- Specify the technical requirements for increasing recovery; design predictable, cost-effective recovery technologies for all classes of plays with significant incremental production potential.

  - Improve the predictability, technical efficiency, and cost-effectiveness of technologies capable of producing substantial volumes of the known remaining oil and gas resources, e.g.:

    -- Targeted infill and directional drilling of oil and gas reservoirs;

    -- Advanced secondary oil and gas recovery techniques; and

    -- Enhanced oil recovery.

  - Validate the technical and economic effectiveness of the above reservoir description and production technologies in order to:

    -- Support aggressive transfer of the technologies to all segments of the producing industry.

-- Promote expectations of increased overall recovery in exploration decisions as well as in evaluations of properties with known remaining oil or gas.

- Ensure effective transfer of cost-effective technologies to operators who hold the most promising properties in such a manner as to encourage timely application.

Resources and Applicable Technologies

♦ The remaining domestic oil resource is large and essential to the nation:

- Of a total of more than 300 billion barrels of remaining oil, two major types can be defined:

  -- *Immobile oil* -- about 230 billion barrels that cannot be produced by conventional recovery; and

  -- *Unrecovered mobile oil (UMO)* -- about 100 billion barrels that could be displaced by water or steam flooding if located and contacted.

- UMO holds great promise for economic development at the oil prices expected in the foreseeable future, especially if UMO can be produced more efficiently than at present.

♦ In a "perfectly homogeneous," relatively thin reservoir containing oil of a viscosity near that of water (or steam), primary and secondary recovery at fairly broad well spacing will produce most of the mobile oil. However, reservoir architecture is commonly complex and fluid properties are variable, resulting in relatively low production efficiency at broad well spacing.

- Reservoir heterogeneities and higher viscosities cause imperfect sweep efficiencies, resulting in two types of unrecovered mobile oil:

  -- *Uncontacted mobile oil* -- compartmentalized oil not in pressure communication with wells; primarily the product of lateral reservoir heterogeneity on the between-well scale.

  -- *Bypassed oil* -- mobile oil in pressure communication with wells but not produced due to:

    - Variations in permeability, with lower permeability zones trapping oil while water sweeps more permeable zones; largely a product of vertical reservoir heterogeneity.

- Adverse mobility ratios or significant gravity effects, as less viscous water (or steam) cuts through, underrides, overrides, and bypasses more viscous or less dense oil.

• Knowledge of reservoir heterogeneities would allow relatively low cost technologies to produce significant portions of the oil through:

-- Targeted infill drilling for uncontacted oil.

-- Permeability contrast reduction (by use of polymers, foams, etc.) and selective well recompletions for oil bypassed due to permeability variation.

-- Polymer-augmented waterflooding and foam diverting agents in reservoirs with adverse mobility ratios or significant gravity effects.

♦ The additional 230 billion barrels of "residual" or immobile oil lies in known reservoirs trapped by viscous and capillary forces that can be overcome only by tertiary or enhanced oil recovery (EOR) -- injection of heat, gases, or chemicals -- which is generally more costly than primary and secondary recovery.

• As much as 60 billion barrels of this resource reside with the remaining mobile oil in unswept reservoir regions; the remaining 170 billion barrels lie in reservoir regions swept by conventional recovery.

• Cost-effective and predictable recovery of this oil also requires detailed knowledge of heterogeneities on the between-well scale and the resultant flow paths in the reservoir.

• Lack of this knowledge is the principal reason behind the unpredictable and economically disappointing performance of the majority of failed EOR projects.

♦ *Essentially the same research is needed to define the critical heterogeneities for either advanced primary/secondary recovery (e.g., infill drilling, permeability contrast reduction) or tertiary recovery.*

♦ Known U.S. oil reservoirs are being abandoned at record rates. As existing wells reach their economic limits and are permanently plugged, vital points of economic access to the remaining resources are lost.

• Recent research suggests that economic access to 30-40% of the national remaining oil resource may already be lost, with the rate of abandonment recently rising from 1% to nearly 2% *per year* of the resource discovered in the U.S.

-- If oil prices remain low and technology advances are not forthcoming, wells accessing 65% of the post-conventional resource will be abandoned by 1995 and could reach 75% by 2000.

-- Even if oil prices returned to the historically high levels of the early 1980s, wells accessing almost 2/3 of the resource could be abandoned by 2000.

-- Production of any significant portion of the remaining oil resource at current and projected oil prices will require use of the *existing* wells and infrastructure; replacing them after abandonment would be prohibitively costly.*

- Thus, there is pressing urgency to conduct the research on reservoir heterogeneity and recovery systems that will permit cost-effective production of the remaining resource before access to it is, for practical purposes, lost.

♦ Moreover, if understanding of reservoir heterogeneities and overcoming their limitations on production were to become routine, higher recovery efficiencies would be expected from economically marginal, new *exploration* prospects, e.g., small and subtle traps, deep, offshore, and Arctic reservoirs.

- To the extent these higher recovery efficiencies become expectations incorporated in evaluation of marginal prospects, more will be explored and developed.

- This development would further increase the potential of conventional, advanced primary/secondary, and tertiary recovery processes.

♦ Further, significant quantities of natural gas are believed to be trapped in known reservoirs by heterogeneities *identical* to those that cause uncontacted oil, the understanding of which would enable increased, cost-effective production.

- As with oil, if improved understanding of gas-trapping heterogeneities can improve recovery from known reservoirs, the effects would be reflected in the evaluation of marginal exploration targets and higher cost unconventional gas resources.

- Increased recovery of domestic gas and its more extensive use, especially in transportation, would directly benefit the environment by reducing CO_2 emissions believed to contribute to global warming.

♦ *Thus, improved understanding of reservoir heterogeneities, technologies for describing them, and technologies for overcoming their effects, are critical and urgent if the technical and economic producibility of U.S. oil and gas resources -- both known and undiscovered -- is to be maximized.*

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*Infill or directional drilling for *purely* uncontacted oil would require the use of existing or replacement infrastructure, but not necessarily of existing wells except for reservoir testing to locate the uncontacted oil. In reservoirs with significant quantities of located, uncontacted oil, plugging in existing wells would not necessarily result in prohibitive costs for redevelopment. Such reservoirs, however, are believed rare.

Constraints on Present Federal Research in Developing and Exploiting Improved Understanding of Reservoir Heterogeneities

- Organization:

  - U.S. oil and gas research has tended to be field-specific (private) or broadly generic but discipline-specific (public).

  - True interdisciplinary research is rare, but essential to the integration of understanding of the production limitations imposed by geological heterogeneities with design of recovery systems to overcome them.

    - It is facilitated by focusing on *specific*, not global, problems.

    - It is enhanced by *clear objectives* obtainable in *specified time* periods.

  - Closest collaboration of geologists, geophysicists, geochemists, geostatisticians, reservoir engineers, and supporting disciplines (e.g., chemistry, physics, mathematics) is necessary for success.

- The specificity/generalization problem:

  - "Generic" research, when successful, requires many steps of translation to be related to specific reservoirs, often costing significant time and limiting applicability.

    - Some "generic" research simply loses relevance, regarded by pragmatic operators and field personnel as inapplicable.

    - Some "generic" research, to be manageable and definitive at the same time, focuses on research topics so small as to have vanishingly little significance in field application.

    - An "each reservoir is unique" attitude devalues all but reservoir-specific research, straining both the federal role and the ability to conduct research cost-effectively for broad application.

  - However, *as extremely promising working hypotheses*, the following can be posed:

    - Hypothesis A (the Producibility Hypothesis): reservoir heterogeneities and resulting flowpaths are determined by geologic history (deposition and diagenesis); knowledge of these flowpaths will permit development of cost-effective recovery technologies and/or methodologies.

- Hypothesis B (the reservoir-to-play Similarity Hypothesis): reservoirs with the same deposition, diagenetic and tectonic histories, collectively considered a "play," exhibit similar heterogeneities, and therefore similar production constraints.

- Hypothesis C (the play-to-play Similarity Hypothesis): reservoirs in similar but separate plays will have similar heterogeneities because of similar depositional histories.

- If these hypotheses prove true, results of research on one reservoir can be generalized to its full play and from one play to other plays, thereby vastly expanding the relevance of the research and accelerating its application.

  - That is, if properly interpreted through an integrating framework, heterogeneity research on *specific*, well selected "specimen" reservoirs can also be *generic* in interpretation to broader classes of other reservoirs and plays, "leveraging" the research for broad application.

  - The specific "similarities" hypothesized may be of several forms, e.g., valid generalizations as to shape, size, or properties of reservoir components or generalized functional relationships between depositional and diagenetic phenomena and the resulting reservoir architecture, flow paths, and other properties.

  - Recognizing substantive differences between reservoirs classes could become important in avoiding errors of overgeneralizing research results, thereby improving the quality of design of extraction processes for specific reservoirs and avoiding "failed" tests of oversold but misapplied recovery systems.

♦ Time orientation:

- Many advanced secondary and tertiary recovery techniques that might be economically viable using existing wells will be unfeasible if these wells must be redrilled or replaced.

- The historic long-term orientation of federal research belies the potential near-term loss of costly access points in known reservoirs as existing wells are being abandoned at accelerating rates.

- The urgency due to well abandonments varies significantly from play to play; for research to be relevant to a particular play, it must yield results before significant abandonment -- sometimes urgently short-term, other times, much longer term.

♦ The "scale of investigation" problem:

- Heterogeneities of interest range from microscopic to miles in dimension.

- Laboratory investigations of small-scale heterogeneities are significant but do not alone reveal extremely important macroscale reservoir architecture.

  -- Larger scale heterogeneities must be examined and interpreted -- interwell areas, well patterns, multi-well sections, and sometimes whole reservoirs.

  -- Higher costs of large-scale investigation cannot be avoided because many of the phenomena of interest exist *only* at large scale.

  -- But, these high costs can be partially mitigated by judicious use of an integrated interpretation framework, studies of modern environments and outcrops, geostatistics, and field case histories (with detailed simulation studies).

- A significant challenge remains as to the proper ways to combine information of different scales and to use it in an integrated form in the design of extraction systems in specific settings.

♦ "Supportive" versus "targeted" research:

- Heterogeneity research must be both basic (e.g., the fundamental nature of the heterogeneities, how they were formed, and how they determine flow paths in the reservoir) and applied (e.g., what specific heterogeneities affect what particular classes of plays and reservoirs and how these effects can be overcome).

  -- The basic-applied distinction is not particularly fruitful in this research.

- To effectively meet the goal and objectives, both basic and applied research must be highly *targeted* on specific plays.

  -- The play-specific focus permits concrete problem definition that can lead to specific and timely solutions.

  -- The play-specific orientation can focus and facilitate concrete multi-disciplinary exchange and the emergence of truly *inter*disciplinary approaches.

- However, "targeted" research requires significant "supportive" research to provide the measurement and interpretation techniques to be used to increase understanding, and the recovery process techniques to overcome the effects of heterogeneities.

  -- Focusing on plays exploits both their similarities (by permitting judicious generalization) and their differences (by avoiding irrelevant side issues).

- The distinction between "targeted" and "supportive" research could permit both to play effective roles in reaching the overall objectives.

• Much of current federal oil and gas research concentrates on research that would here be termed "supportive" in the belief that it is desirably "generic," "basic," or "long-term, high risk."

  - Such research must continue, but must be seen in its appropriate context of supporting the targeted research that more directly addresses the goal and objectives.

  - Targeted research focusing on specific plays will encounter technical constraints in measurement, interpretation, modeling, and various recovery technologies; *relaxation or removal of these constraints could become the objective of the supporting research, providing a focus that assures specific and relevant application.*

• "Targeted" research has historically been de-emphasized due to apparent lack of generalization and high cost.

  - If the Similarity Hypotheses prove true, however, highly targeted research can be generalized through use of an integrated, interpretive geologic classification framework.

  - High costs can be mitigated by cost-sharing with states and/or operators.

♦ The quantity of and differences among plays:

• Prospective plays in the U.S. number in the hundreds, with dozens of different depositional/diagenetic types or classes.

• Targeted, play-specific research requires choices by federal officials as to which plays will be studied.

• Several relevant criteria for selection could be applied, including:

  - Total resource (oil or gas) remaining.
  - Technically producible resource remaining.
  - Economically producible resource remaining.
  - Urgency based on loss of economic reservoir access through well abandonments.
  - Generalizability based on the numbers and magnitudes of plays with comparable depositional histories.
  - Equity in distribution of research to most immediately benefit respective geographic areas or industry types (e.g., majors versus large independents versus smaller independents).

- A most appropriate criterion might be the magnitude of the "gain from R&D" -- the incremental reserves added due to successful completion and application of the research -- as tempered by the other criteria.

♦ Technology transfer:

- Present technology transfer mechanisms (publications and symposia) serve primarily the most sophisticated audiences.

  -- Other researchers, public and private.
  -- Major operators with R&D staffs.

- Broadened technology transfer, especially of "targeted" research, could reach broader audiences faster and result in more rapid and widespread application of new techniques.

  -- New audiences, approaches, and formats for information may be needed to reach specific audiences.

- If the Similarity and Producibility Hypotheses prove true, transfer of demonstrably effective techniques from the studied and tested specimen reservoir to other reservoirs in the same play and from its play to others of the same class could be the key strategy.

- The researchers involved with the specimen reservoir could act as key agents of technology transfer, supported by an integrative and interpretive analytical structure.

♦ Monitoring of progress:

- Historically, the "long-range, high-risk" nature of federal oil and gas research has precluded direct monitoring of impacts; the response time was too long.

  -- Focusing on specific plays, some with immediacy established by imminent abandonments, would permit direct measurement of R&D impact, e.g., slowed abandonments, new drilling, projects initiated, reserves added, production increased.

  -- Such monitoring could serve as direct feedback to the program to evaluate the effectiveness and relevance of its research and technology transfer and could direct "mid-course corrections" to assure meeting its objectives.

Research Requirements to Overcome the Constraints

♦ Federal R&D to satisfy the goal and objectives must be designed to overcome the foregoing constraints.

♦ The requirements, then, are as follows:

- R&D must be *committed* to increasing the producibility of domestic oil and gas.

- R&D must be truly *interdisciplinary*, requiring a close, focused collaboration of all relevant disciplines.

- This interdisciplinary approach can be established and enforced by emphasizing the necessary *targeted research*, focusing on the heterogeneities and production problems of specific, well-selected plays and reservoirs.

  -- *Supportive research* must continue, but be more specifically directed toward overcoming the problems and technical constraints being defined in the targeted research.

- The plays and reservoirs for targeted research must be carefully selected based on explicit criteria.

  -- Such selection requires detailed analytical support.

  -- This analytical support, moreover, is also the key to "extrapolation" or generalization from one play to those that are similar and to aggressive technology transfer.

- The results from the plays selected for targeted research must be interpreted and generalized through an explicit framework based on geologic deposition and diagenesis.

- The specific research approaches to be applied to the selected plays must reflect the particular issues affecting the reservoirs of these plays, including:

  -- The particular geological features constraining the production of known oil and gas;

  -- The technologies applicable to overcoming these specific constraints;

  -- The urgency of application as defined by the projected rate of abandonments; and

  -- The economic conditions (prices, costs, and taxes) expected to prevail as abandonment approaches.

- The results of the research must be transferred aggressively and rapidly, first within the plays under investigation, then to those with greatest geologic similarity, and then, by degree, to those with less similarity.

- The impact of the research within the fields and plays directly studied *and* those subject to valid generalization must be monitored and evaluated, with appropriate modifications to program structure and content to maximize effectiveness of the research.

A Research Strategy to Meet the Objectives and Requirements (See Figure A1, Summary Work Breakdown)

- ♦ A *research strategy* to meet the goal and objectives and to satisfy the foregoing requirements would *utilize interdisciplinary, play-specific task forces to test the key hypotheses*.

  - *The core of the program would be a number of interdisciplinary geologic-engineering task forces focusing on the producibility of specific plays or classes or plays, supported by more discipline-specific research and program integration functions.*

  - Best available information and analytic tools would be used to *establish priorities* among specific plays and classes of plays for *highly targeted* research.

  - The immediate research objective of the strategy would be to *test the two Similarity Hypotheses*, in carefully selected, high priority plays.

    -- Hypothesis B: Can the description of heterogeneity (internal architecture, flow paths, barriers, location and condition of the oil and gas) in well selected *specimen* sites be generalized to other reservoirs in the same play?

    -- Hypothesis C: Can the description of the heterogeneity in one play (or from its specimen reservoir) be generalized to the reservoirs of plays of the same type of depositional, tectonic, and diagenetic history?

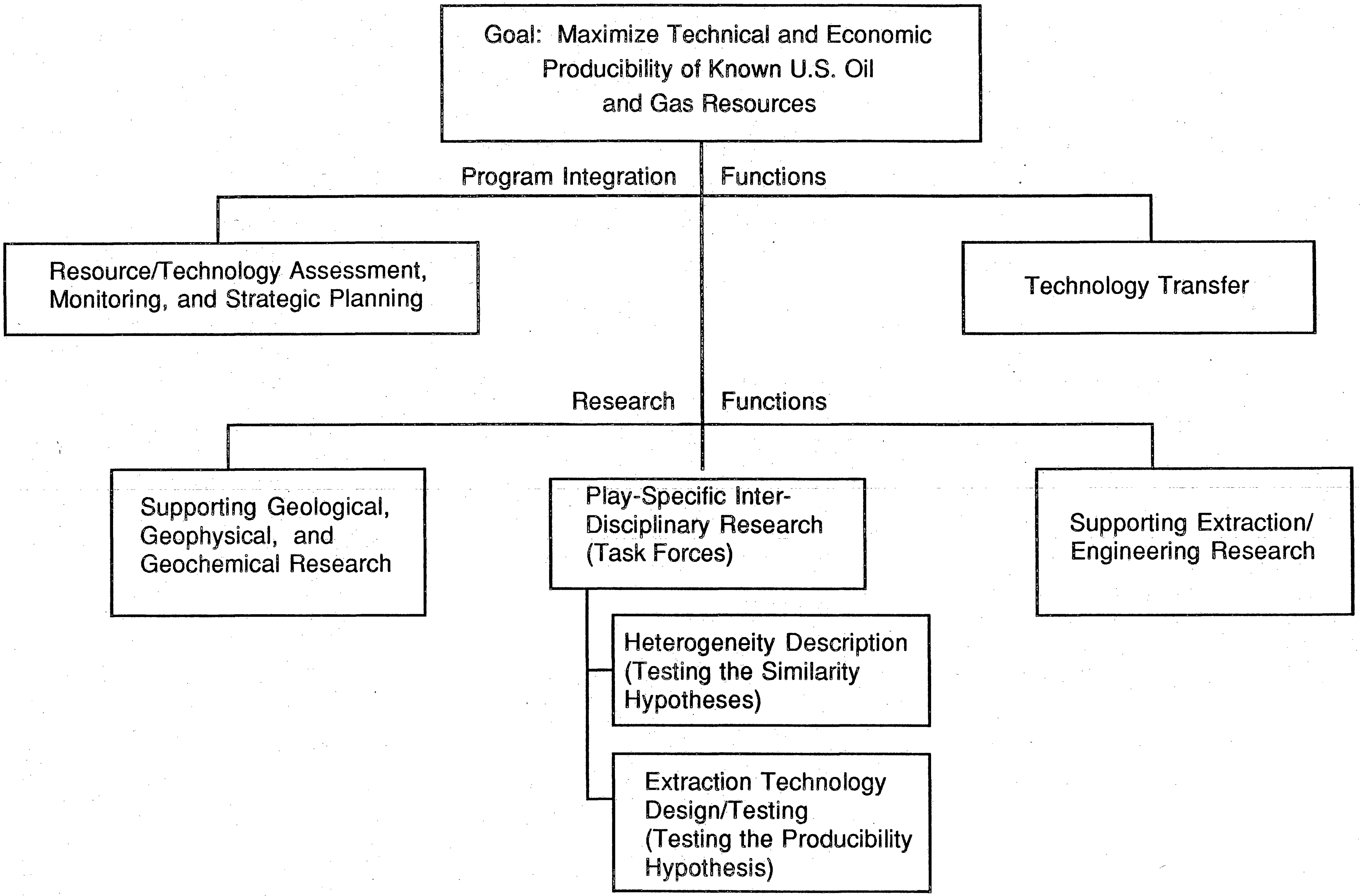
    -- The value of this hypothesis testing would be gauged by increased understanding and the usability of this understanding in designing cost-effective recovery systems.

  - As these hypotheses are being tested and adequate descriptions of the heterogeneity of the selected reservoirs becomes available, the strategy is to *test the Producibility Hypothesis* (A): Can improved understanding of heterogeneity increase cost-effective producibility?

    -- This strategy would include design of cost-effective recovery systems and their testing in the laboratory, by simulator, and, ultimately, in reservoir tests.

    -- The value of testing this hypothesis would be increased cost-effective producibility.

Figure A-1: Summary Work Breakdown Structure for Federal Oil and Gas Research



- As these two steps test the key hypotheses (and assuming they prove true), these functions evolve into *play-specific heterogeneity description* and *extraction technology design/testing* and turn to exploiting this knowledge in increasing producibility in the play studied and in similar plays.

  -- As this progress is made, research in the next highest priority play or classes of plays can be initiated.

- As this highly targeted, interdisciplinary research is being conducted, technical constraints that limit progress will become identified; relaxation of these constraints would be defined as the technical objectives for *supporting research* of a more disciplinary nature in geology, geophysics, geochemistry, reservoir engineering, and related fields.

  -- The value of supporting research would be measured by the extent important constraints are relaxed.

- As targeted and supporting each research yields results and products, aggressive *technology transfer* will make them available to operators and others (e.g., consultants and service companies) who can make use of these results, especially in the class of plays being investigated.

  -- The value of technology transfer would be measured by the extent technologies are applied and reserves and production are increased.

- Applications of research results and resultant increases in reserves and production will be closely *monitored*, and problems anywhere in the strategy will be identified for correction.

  -- Periodic, systematic reappraisals would be scheduled.

  -- The analytic tools used in the original prioritization and selection of target plays would be updated and revised to incorporate the new understandings and data as they become available.

  -- The value of such monitoring and adjustment lies in maintaining the integration and high quality of all components of the strategy.

♦ These components are expected to be overlapping, continuing, and iterative for optimal program achievement.

♦ The specific work of each component can be described in general, although details must await the selection of specific plays.

♦ Each of the major components of the strategy is discussed in somewhat greater detail below; the five parts of Figure A-2 illustrate the progression of the research logic flow and Figure A-3 provides a more detailed, prototype Work Breakdown Structure.

Resource/Technology Assessment, Monitoring, and Strategic Planning (See Figure A-2(a).)

- This component weighs the initial priorities based on detailed analysis, develops the strategic plan, and monitors progress of the other components.
  - The priorities and strategy are expected to be revised as new information becomes available.
- Preliminary prioritization would proceed immediately on the basis of best available information as analyzed through the updated Tertiary Oil Recovery Information System (TORIS).
  - Enhance the database and models.
    - Classify the reservoirs by geologic type and play; add development history, production, and any other needed data.
    - Peer review and modify or confirm TORIS models for UMO recovery and recent updates in EOR.
  - Estimate the values of the key criteria for each play.
    - Analyze the technical and economic potential of UMO recovery and EOR (singly or in combination) for each class assuming (i) business-as-usual and (ii) upgraded geological/technological capability; define the difference between (i) and (ii) as *incremental economic production attributable to enhanced capability*.
    - Estimate the amount of incremental reserves and production lost to abandonments as a function of time and economic conditions.
  - Group plays into classes based on deposition system (with subclasses based on diagenesis and tectonics).
  - Rank classes of plays and the plays within each class by the criteria of incremental economic production due to enhanced capability, urgency, and other criteria, possibly using a systematic multi-dimensional ranking technique.
  - Select the highest priority classes and plays up to the number permitted by the available budget.
  - Organize task forces for each high priority class of plays and assign them to work on the highest priority play in the class.
- TORIS is currently capable of assessing the full oil resources in the states of Texas, Oklahoma, and New Mexico.
  - Together, these three states account for 41% of the remaining oil resource.

Figure A-2 (a) Strategic Logic Flow for Federal Oil and Gas Research:

Prioritization and Strategy-Setting

RESOURCE/TECHNOLOGY ASSESSMENT, MONITORING, AND STRATEGIC PLANNING

- Enhance Data and Models
- Estimate Criteria Values by Play
  - -- Potential Incremental Reserves, Production
  - -- Time to Abandonment

RESOURCE	TECHNOLOGY Current	Advanced
Mobile Oil		
Immobile Oil		
Gas		

- Group Plays by Depositional Class
- Rank Classes by Criteria
- Select Classes and Plays; Design Strategy for Each (Timing, Geological Approach, Extraction Technologies)
- Organize Task Forces for Each Priority Play
- Monitor progress and update data and models

Data from Monitoring and Heterogeneity Description

Selection of Priority Classes and Plays

(To Heterogeneity Description)

- Oil reservoirs in other states could be readied for the analysis in a period of months.

- A preliminary analytical system for *natural* gas could be synthesized from existing models and data in about one year; within two years, the gas model could approximate the capabilities exhibited by TORIS for the oil resource.

♦ While TORIS (or a comparable gas model) should be used where possible, expert judgement could be substituted for detailed analysis in the interim, to be confirmed by detailed analysis when available.

♦ As the research proceeds:

- Improved and expanded data from the heterogeneity research component will be incorporated as updated to TORIS data.

- Similarly, as extraction systems are tested, TORIS recovery models will be updated.

- As the task forces move research products through technology transfer, their application will be monitored in the appropriate plays.

♦ Monitoring will consist of collecting and interpreting data on infill drilling and injection programs initiated in the priority classes of reservoirs and comparing these to lower priority classes of reservoirs or all reservoirs, nationwide.

- This provides a direct measure of the impact of the research on the goal of increasing producibility of the resource and, ultimately, production.

- Monitoring data on the performance of each component of the strategy to evaluate their progress and support "mid-course corrections."

Heterogeneity Description (See Figure A-2(b).)

♦ The first objective of the Heterogeneity Description component of the strategy is to test the two Similarity Hypotheses for the highest priority plays and classes of plays.

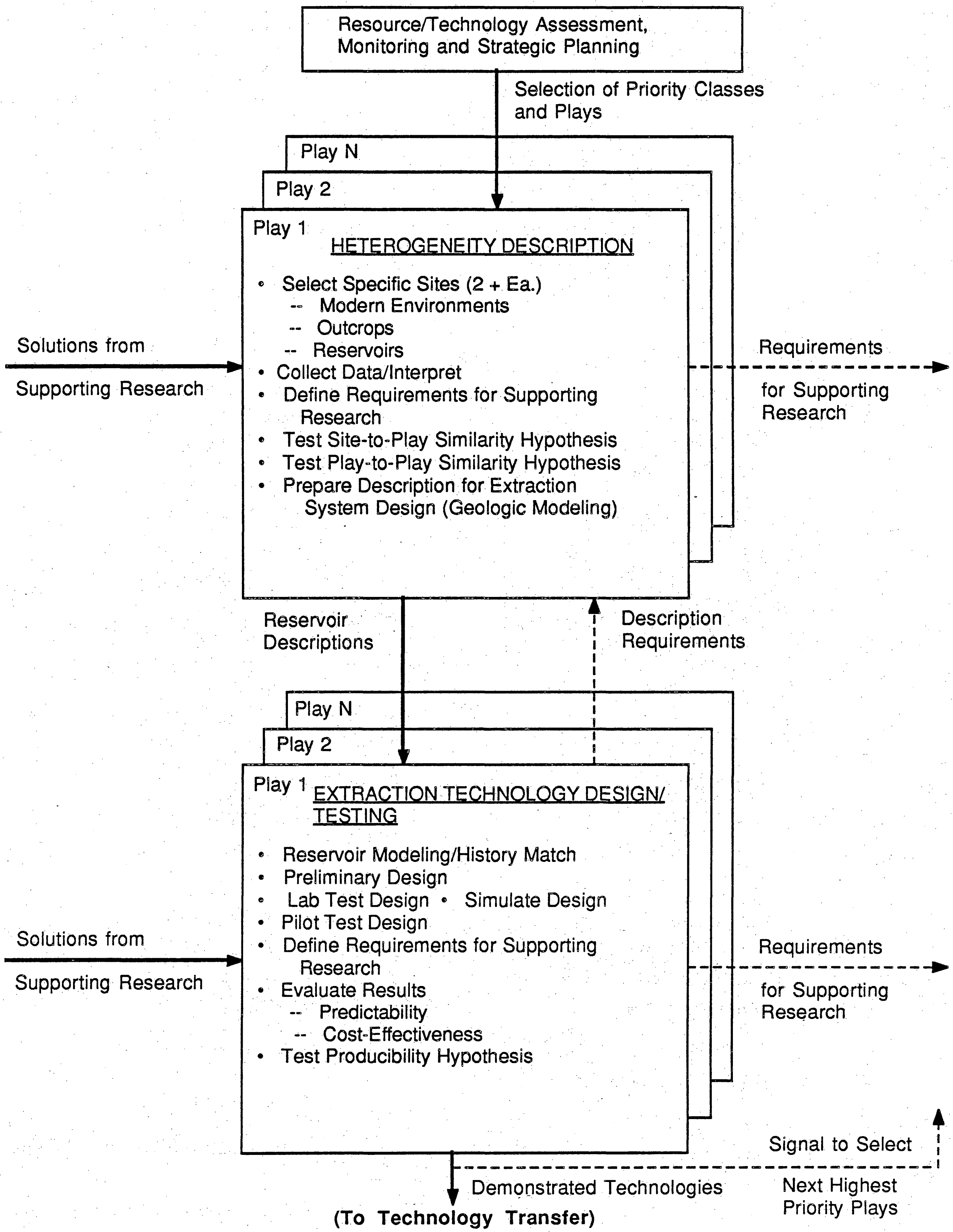
- In doing so, the reservoir architecture, barriers, flow paths, location and condition of oil and gas will be refined for use in developing extraction systems.

♦ The hypothesis testing will be conducted at three levels for each class of plays:

- Specific "sites" for research at each of three "levels" for the highest priority classes; for each class, two or more specific "sites" to address scales, styles, and dimensions of reservoir heterogeneity at the following "levels":

Figure A-2 (b) Strategic Logic Flow for Federal Oil and Gas Research:

Hypothesis Testing



- Modern environments
- Outcrops
- Reservoirs

• More classes may be selected for analysis of modern environments and outcrops than for reservoir studies as these are less costly and faster to study and may yield useful preliminary results; *however,* definitive results require detailed work at the actual reservoir level.

♦ Modern environments.

• Compilation of areal and vertical sediment patterns with respect to potential hydrocarbon flow units and barriers.

• Statistical analysis and synthesis of data.

• Possible development of formal models of depositional processes; models from other disciplines, e.g., geography, climatology, civil engineering, may be adapted.

♦ Outcrops.

• Detailed architectural description of volumetrically important reservoir types, emphasizing geometry and continuity of flow units and flow barriers.

• Definition of vertical and lateral variability in petrophysical parameters.

• Statistical synthesis of data including methods for estimating, assigning, and averaging rock properties.

• Mathematical descriptions of multi-component systems.

• Near-outcrop flood tests with fluid flows monitored at outcrops.

♦ Reservoirs.

• Delineation and quantification of heterogeneity with research at the inter-well and single-well scale:

• Inter-well scale research.

-- Geological analysis.

- Develop methods for rapid identification and delineation of heterogeneity types from cores and well logs.

- Integration of geological flow units with between-well seismic, engineering, and production data.

- Reinterpretation of existing well logs.

- Integration of data from core and existing and new well logs.

-- Geophysical analysis.

- Three-dimensional surface seismic techniques.

- Between-well seismic and electrical techniques.

- Well-to-surface seismic techniques.

-- Engineering analysis.

- Tracers.

- Pressure transient testing.

- History-matching through reservoir simulation.

-- Horizontal wells for deterministic quantification of inter-well variability (selectively).

• Single-well scale research.

- Rock and fluid properties derived from higher resolution, deep investigation logs, tracers, and/or log well tests -- and their integrated interpretation.

- Improved methods for incorporating diagenesis into the flow unit concept.

♦ Detailed, integrated reservoir characterization.

-- Quantification of heterogeneity.

- Inference and quantification of continuity and anisotropy of flow properties.

- Scale up of core and porosity information and scale down of seismic descriptors to the inter-well level while preserving geologic reality.

♦ At each level, the Similarity Hypotheses for highest priority class(es) will be tested:

- Results at the comparable sites for each level will be contrasted to determine whether and how the hypothesis of similarity applies -- reservoir-to-play and play-to-play.

- Hypotheses can be disproven for a given class at any level; the results of the faster work (modern environments and outcrops) would expedite program modification or selection of the next highest priority class if a higher ranked class is disproven.

♦ As each class is tested, work is commenced in the next highest priority class(es) to the extent permitted by the budget.

♦ As technical constraints are encountered, requirements for supporting research will be defined.

♦ Active operator collaboration will be essential to rapid progress, especially at the reservoir level in providing data or permitting access for collecting, new data and testing concepts. Incentives to elicit such collaboration might be considered.

Extraction Technology Design/Testing (Also illustrated in Figure A-2(b).)

♦ The Extraction Technology Design/Testing component tests the Producibility Hypothesis by using the detailed reservoir heterogeneity description to design recovery systems and testing their *predictability* and *cost-effectiveness*.

♦ *The specific technologies to be considered will vary with the reservoir and play properties, economic conditions, and the time available before access to the resource is lost through well plugging.*

♦ In general, working closely with the geological description of the reservoir, four steps would be followed:

- Reservoir modeling history matching for iterative confirmation of the geological description and the simulator "set-up."

- Design of specific recovery system(s) and approach(es).

- Laboratory testing of the approach(es).

- Testing of the approach(es) by formal simulation, followed by refinement of the design.

- Field testing of the design (generally by small scale pilot test) with indepth diagnostics to evaluate predictability and cost-effectiveness.

♦ As positive results are obtained from such tests, they will be converted into forms suitable for technology transfer to all relevant audiences in the tested plays.

- Assuming the Similarity Hypotheses have been demonstrated in the Heterogeneity Description component, they must also be tested with respect to the Producibility Hypothesis.

  -- If the Producibility Hypothesis is thus shown to be generalizable to a full class, technology transfer can be expanded to the other plays in the class.

- As each studied class progresses to the point of technology transfer, the next highest priority classes and plays can be selected and the process repeated to the extent available budgets permit.

♦ As in Heterogeneity Description, as technical constraints on the cost-effectiveness of available extraction systems are encountered, requirements for supporting research will be defined.

Technology Transfer (See Figure A-2(c).)

♦ This component is designed to quickly and effectively communicate the results, findings, and products of the research to the target audiences who can use them:

- Major and independent operators.
- Consulting engineers and geologists.
- Service companies.
- Other researchers.

♦ Numerous channels for technology transfer will be used and evaluated for effectiveness, e.g.:

- Publications.
- Workshops and symposia.
- Computer-aided "expert systems."
- Assistance to "petroleum extension agents" operating through state universities and geological survey.

♦ A critical part of the monitoring function (above) will be to ascertain the extent to which the research products transferred to the target audiences are being put to use, resulting in increased U.S. reserves and production.

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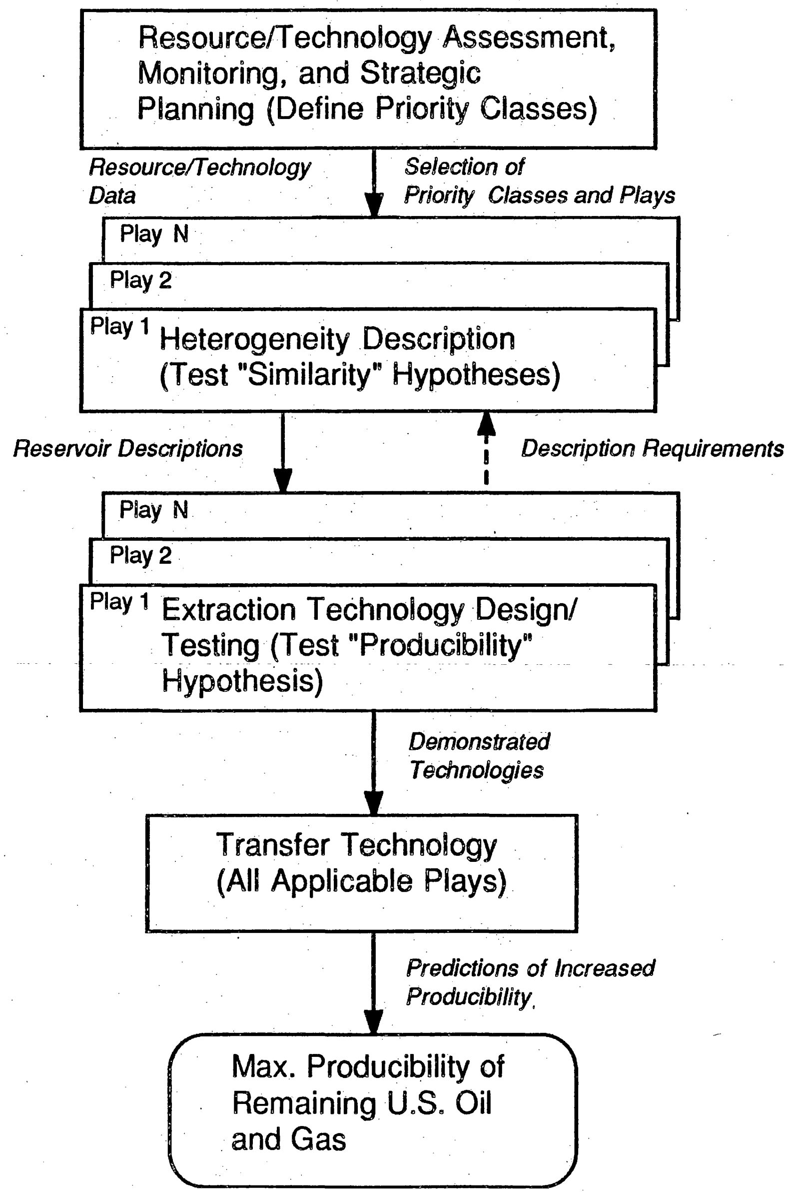
Figure A-2 (c) Strategic Logic Flow for Federal Oil and Gas Research:

Relationship of Core Program to Goal



Supporting Research (See Figure A-2(d).)

- Supporting research is designed to respond to *specific requirements* as defined by the technical constraints encountered by the play-specific task forces.

    - This provides criteria of relevance and value previously absent from federal "generic" and "fundamental" research.

    - As certain constraints become recognized as applicable to numerous classes of plays, the concept of "generic" research is approximated, but the research remains focused on solving real, articulated problems that limit the ability of the play-specific task forces to meet the program's objectives and goal.

    - In the early stages, fairly strict application of the criterion of whether the supporting research truly seeks relaxation of specific, technical constraints (defined as important by the task forces) should be applied to permit sharp focusing of the supporting research.

    - While multi-play supporting research would be definable as "generic," the nature of the specific constraints (and time available to relax them), would dictate whether "fundamental" or "applied" supporting research is required.

- *The specifics of supporting research cannot be defined until the task forces define the critical constraints; however, it is probable that much of the federal program's present research would be germane.*

- For purposes of illustration, supporting research is considered to be of two types -- geological, geophysical, and geochemical research and extraction engineering research.

- Examples of supporting geological, geophysical, and geochemical research:

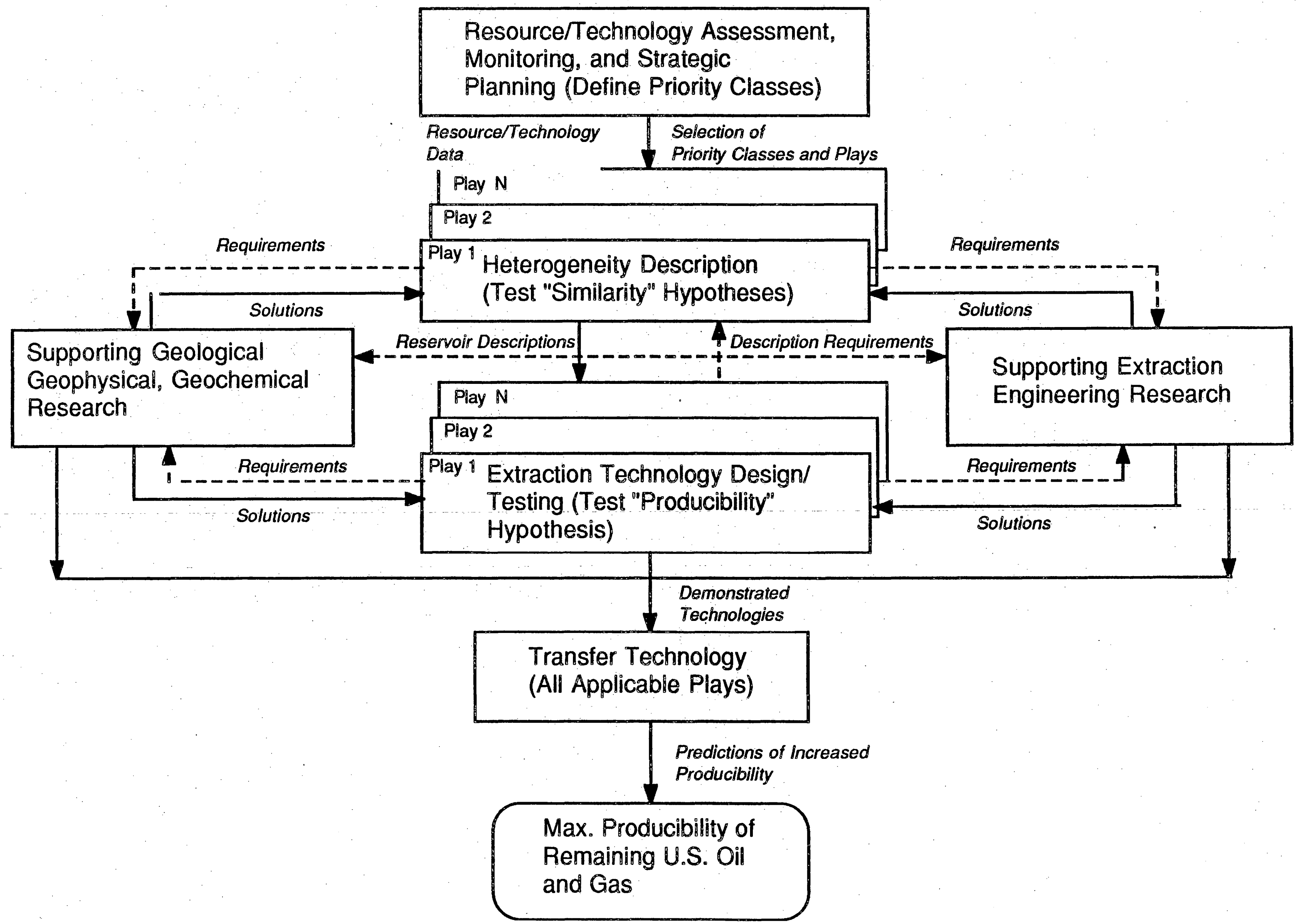
    -- Advanced instrumentation.

    - High resolution seismic, areal and downhole.
    - Logging-through-casing.
    - Measurement-while-drilling.
    - Novel reservoir instrumentation.

    -- Advanced interpretation techniques.

    - Geostatistics.
    - Geological scaling and modeling.
    - Well testing.
    - Integrated interpretation methods and protocols.

Figure A-2 (d) Strategic Logic Flow for Federal Oil and Gas Research: Role of Supporting Research



-- Fundamental geoscience research.

  - Reservoir chemistry and physics.
  - Rock-fluid systems.
  - Hydrology and environmental protection.

♦ Examples of supporting extraction engineering research:

  -- Reservoir performance simulation (oil and gas) research.

  -- Advanced primary/secondary recovery systems (oil and gas).

    - Completion/stimulation techniques.
    - Permeability contrast reduction.
    - Waterflood/steamflood mobility control.
    - Drilling--directional, horizontal; optimization.
    - Operations and work-overs.

  -- Advanced tertiary recovery.

    - Gas flooding.
    - Chemical flooding.
    - Thermal flooding.
    - Combination processes.
    - Microbial flooding.
    - Novel tertiary processes.

  -- Advanced environmental protection (oil and gas).

    - Reversible well plugging.
    - Environmentally acceptable disposal of drilling wastes and produced fluids.

♦ Progress in supporting research will relax technical constraints encountered by the task forces but will also often represent major contributions in its own right, so will also be "packaged" for technology transfer.

♦ Comparisons, interpretations, and results will be made available as early as possible through diverse media, allowing operators and other petroleum professionals to make use of the information. These publications and presentations will attempt to advance valid generalizations to reservoirs of the priority classes that were *not* specifically studied as well as those that were.

Program Integration (See Figures A-2(e) and A-3.)

♦ Monitoring data would flow back to the planning function from both the major program components and from the "real world" of U.S. reservoirs.

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Figure A-2 (e) Strategic Logic Flow for Federal Oil and Gas Research: Overall View

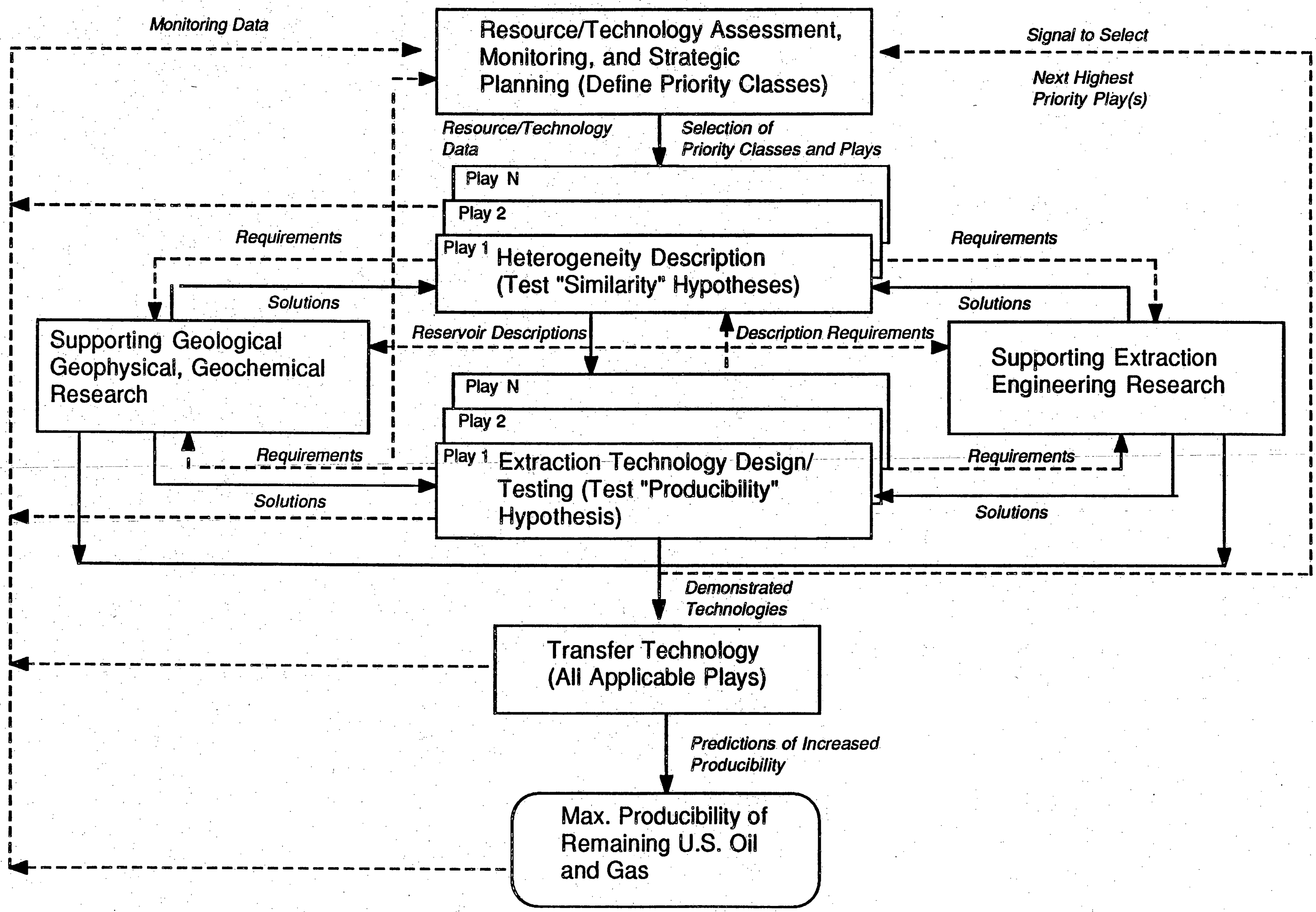

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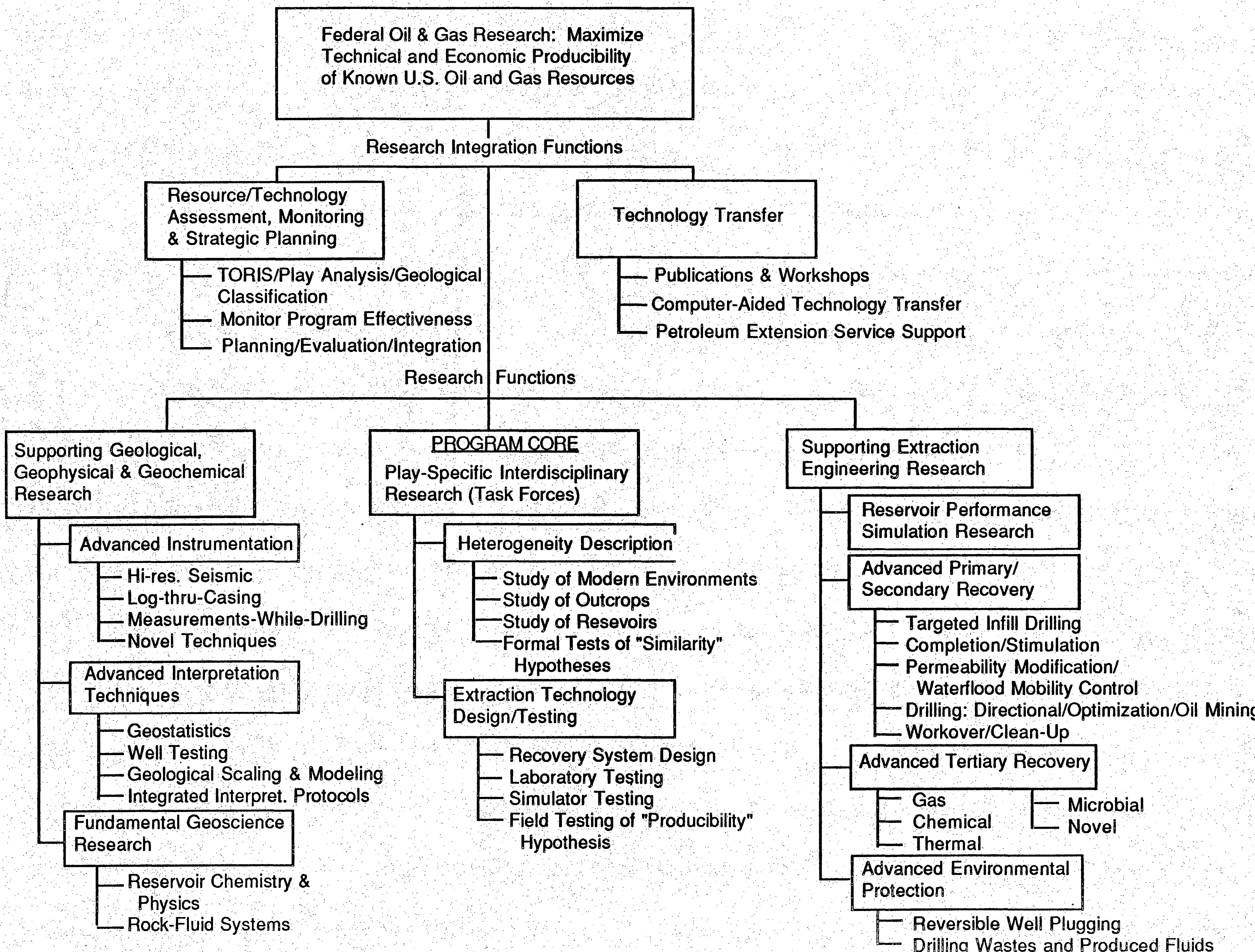
Figure A-3: More Detailed Prototype Work Breakdown Structure for Federal Oil and Gas Research



Monitoring data pertaining to applications of new technologies, and increases in reserves and production from the studied classes of plays would directly measure progress toward the program goal.

-- The absence of such progress may indicate a lack of effectiveness or timeliness in one or more of the program's major logical components.

- Data pertaining to the performance of the respective components provides the basis for evaluation and corrective action.

♦ Seen as an integrated whole, the program would require substantially closer integration than is now present.

- The close interaction of the program components, clear criteria of progress in each, and the feedback of data to support evaluation of all necessitate close program integration.

- The requirement for integration, however, is not a requirement for a high degree of centralization.

- Critical to the logic of the suggested program is a high degree of decentralization according to the classes of plays defined as the critical focus of the research and the key to progress toward the program goal.

- The combined need for close integration of a program with a decentralized research focus will impose management challenges not previously experienced.

Conclusions

♦ The organization and specific focus of the central task forces would provide a bridge across disciplinary lines and would assure the interdisciplinary and practical approach required to convert R&D into improved producibility.

♦ At the same time, the supporting research can be placed in the practical context of responding to the requirements defined by the task forces but can exploit the strengths of discipline-specific research.

♦ In addition to benefiting the nation, the work of task forces, being tailored to specific plays, directly benefits the state, region and local operators. Cost-sharing (via Memoranda of Understanding or consortia) is thus appropriate and could be more readily arranged than "generic" research applying broadly to all, but specifically to few.

♦ Further, while providing a broad uniformity in objectives and general approach, the suggested strategy tailors the geological, geophysical, and engineering work to the specific problems of individual, high priority plays.

- As the focused, tailored, practical solutions become available, technology transfer can also become more focused, tailored, and practical, speaking directly to operators, technical professionals, and service companies facing the specific challenges in particular, high-priority plays.

- The foregoing strategy outline could be seen as an overview of the entire Fossil Energy program in oil and gas geosciences and extraction research.

    - It would require significant collaboration among existing headquarters and field units to define respective responsibilities and integrative linkages;

    - It would require significant management coordination to create, implement, and evaluate these plans without unduly constraining the tailored play-specific task force research; and

    - It would require the understanding and favor of other DOE units, OMB, and key Congressional leaders and subcommittee staffs.

- But, the outlined strategy constitutes a significant departure from the current program --

    - A departure with a new focus on the most pressing issues -- reservoir heterogeneity and the urgency imposed by the impending abandonment of wells.

    - A departure with significant promise of meeting the goal -- increasing the economic and timely producibility of the nation's oil and gas resources.

APPENDIX B
GLOSSARY OF GEOLOGIC TERMS

anticline. In its simplest form, an anticline is an elongated fold in which the sides or limbs slope downward away from the crest. This simple form may be greatly complicated during progressive stages of folding. In a normal sequence of bedded rocks, the oldest beds are in the core of the anticline and the youngest lie on the flanks.

back-barrier facies. The depositional environment consisting of sediments deposited landward of and protected by a barrier island. Back-barrier subenvironments, include lagoon, bay, washover fan, tidal delta, tidal flat, marsh and estuary. Most back-barrier sediments, except for those in washover fan and tidal delta environments, are muddy, because they are deposited in low-energy conditions.

barrier-core facies. The sand skeleton of the barrier island, deposited parallel to depositional strike. The core is a composite of beach, dune, and upper-shoreface sands. These sands are typically well- to moderately well-sorted, because they are deposited in high-energy conditions along the shoreline.

barrier island. A narrow elongate sand ridge rising slightly above high-tide level and extending generally parallel with the coast, but separated from it by a lagoon. Modern examples are Galveston Island on the Texas Gulf Coast and Cape Hatteras on the Atlantic Coast.

carbonates. Mineral compounds characterized by a fundamental anionic structure of CO_3^{-2}. Calcite and aragonite, $CaCO_3$, are examples of carbonates.

clastics. Pertaining to rocks or sediments composed principally of fragments derived from pre-existing rocks or minerals and transported some distance from their places of origin. The most common clastics are sandstone and shale.

deposition. The act or process of accumulating natural materials into sediments. Deposition includes mechanical settling of material from bodies of water and ice or from the air, the precipitation of material from solution by evaporation and other chemical actions, and the accumulation of organic material through the life processes of plants and animals.

depositional system. A group of facies linked by a depositional environment and associated processes.

Note: The definitions supplied in Appendix A are drawn primarily from: Stokes, W.L. and Varnes, D.J., "Glossary of Selected Geologic Terms", Colorado Scientific Society, 1955; Bates, R.L., and Jackson, J. A. (eds.), "Dictionary of Geological Terms," 3rd ed., American Geological Institute, 1984; Galloway, W.E., and Cheng, E.S., Reservoir facies architecture in a microtidal barrier system

- Frio Formation, Texas Gulf Coast, The University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 144, 36 p.

diagenesis. All changes undergone by a sediment after its initial deposition, exclusive of metamorphism. It includes processes (such as compaction, cementation, dissolution, and replacement) that occur under conditions of pressure and temperature that are normal at shallow depths in the outer part of the earth's crust.

facies. A facies is a three-dimensional body of rock whose environmental origin can be inferred from a set of observable characteristics. The features on which facies are named and recognized are usually lithologic (lithofacies) or biologic (biofacies). The lithologic designation predominates in this report. The term applies to a specific rock unit; a facies within the specific unit then designates some particular or general feature by which a part differs from other parts deposited at the same time. Example: deltaic facies of the Green River Formation.

fusulinid. Any of an important group of extinct, marine, one-celled animals (Class Sarcodina, Phylum Protozoa) that have left an extensive fossil record for late Paleozoic time. Fusulinids are characterized by a multi-channeled calcareous test, commonly resembling a grain of wheat. Because of their small size, they are easily recovered from well cuttings and have proved of great value in correlation of oil-bearing Pennsylvanian and Permian age rocks.

grainstone. A grain-supported sedimentary carbonate rock containing no mud.

grainstone-dominant facies. A reservoir rock volume consisting primarily of small carbonate grains cemented together, with only a minor amount of mud. This type of rock represents depositional environment in which most of the mud-sized particles that may have previously existed have been winnowed away by high-energy conditions.

lithology. The description of rocks on the basis of such characteristics as color, mineralogic composition, grain size, grain type, and grain distribution.

mudstone. A mud-supported sedimentary carbonate rock containing less than ten percent grains.

nongrainstone facies. The reservoir rock volume dominated by mud-supported carbonate, consisting primarily of mudstones and wackestones. This type of rock reflects a relatively low-energy depositional environment.

oil play. A family of oil reservoirs or fields sharing a common geologic history as defined by present day reservoir similarities. The most important parameters in play definition are reservoir origin, trap style, and source rocks. Basic geologic, engineering, and production attributes are also considered in the designation of a play. The importance of a play is that its component fields are considered a geologic "unit" from which play to play comparisons can be made.

oolite. a sedimentary rock, usually a limestone or dolostone, made up of small, rounded accretionary bodies, or ooliths, cemented together. Ooliths resemble fish eggs, with a diameter of 0.25 to 2.0 mm. The concentric coatings of these grains precipitate inorganically around a nucleus.

packstone. A grain-supported sedimentary carbonate rock containing some matrix of carbonate mud.

sediment. Solid, natural material that has settled down from a state of suspension in water, air, or ice.

shoal. A submerged ridge, bank, or bar of sand or other unconsolidated material, rising from the bed of a body of water to near the surface.

strandplain. A shore typically consisting of narrow, sand, beach ridges separated by wide bands of fine-grained sediments built seaward by waves and currents, and continuous for long distances along the coast. Modern examples are the chenier plains in Southwest Louisiana and the beach ridges along Nayarit, Mexico.

tectonics. A branch of geology dealing with the broad architecture of the outer part of the earth, that is, the major structural or deformational features and their relations, origin, and historical evolution.

tidal flat. An extensive, nearly horizontal, marshy or barren tract of land that is alternately covered and uncovered by the tide, and consisting of unconsolidated sediment.

tidal-inlet facies. Erosionally bounded, dip-oriented deposits that accumulated in tidal channels cross-cutting the barrier-island. This facies is characterized by 1) an erosional base and coarse debris lag, 2) an upward-fining sequence, 3) a superimposed upward-coarsening sequence, and 4) a cap of beach deposits.

wackestone. A mud-supported sedimentary carbonate rock containing greater than ten percent grains (particles with diameters greater than 0.2 mm).