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MAJOR PROGRAM ELEMENTS FOR AN ADVANCED GEOSCIENCE OIL AND GAS RECOVERY RESEARCH INITIATIVE

Program Study Summary Report:

Recommendations and Research Activity Priorities

October 1989

Prepared on Behalf of the

Office of Fossil Energy

U.S. Department of Energy

Geoscience Institute for Oil

and Gas Recovery Research

A National Consortium

Bartlesville Project Office

U. S. DEPARTMENT OF ENERGY

Bartlesville, Oklahoma

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By

Geoscience Institute for
Oil and Gas Recovery Research
The University of Texas at Austin
University Station, Box X
Austin, TX 78713-7508

A National Consortium

University of Alabama
University of Alaska
Colorado School of Mines
University of Houston
Illinois State Geological Survey
University of Kansas
University of Kentucky
Louisiana State University
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University of Wyoming

Prepared on Behalf of the Office of Fossil Energy
U.S. Department of Energy

FOREWORD

This publication, issued by the U.S. Department of Energy (DOE), Bartlesville Project Office, is the first volume of a two-volume set prepared for DOE by the Geoscience Institute for Oil and Gas Recovery Research. It contains the Institute's summary report and recommended activities and priorities for a geoscience oil and gas recovery research initiative.

Volume II -- Technical Subcommittees Program Summary, with an accompanying appendix, REGIONAL TECHNICAL FORUMS REPORT, will be published in the future as reference material for the present publication. For information regarding these publications, contact:

U. S. Department of Energy
Bartlesville Project Office
Technology Transfer
P.O. Box 1398
Bartlesville, OK 74005
918/337-4293 Commercial
FTS 745-4293

University of Alabama
University of Alaska
Colorado School of Mines
University of Houston
Illinois State Geological Survey
Indiana University
University of Kansas
University of Kentucky
Louisiana State University
University of Michigan
Mississippi State University
New Mexico Institute of Mining and Technology
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Geoscience Institute Technical Coordinators

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F. J. Lucia	Geological Coordinator
M. A. Miller	Engineering Coordinator
E. B. Neitzel	Geophysical Coordinator

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Executive Summary

Background

The United States is facing a critical shortage in the supply of domestically produced oil. The lack of an adequate domestic supply of oil threatens our national security. In the past 2 years, following the downturn in the oil and gas industry, crude oil imports have risen sharply to over 42 percent of daily demand in 1988 and are projected to exceed 50 percent by the early 1990's. This trend is occurring despite the presence of a huge oil resource that remains untapped in already discovered fields.

It is estimated that over 325 billion barrels (Bbbl) of unrecovered mobile and immobile oil are present in existing reservoirs (NPC, 1984). In addition to this oil resource, more than 460 trillion cubic feet (Tcf) of inferred, extended, and low-permeability natural gas resources occur in existing fields (Finley and others, 1988). These known U.S. oil and gas resources occur in complex, heterogeneous reservoirs that have not been uniformly swept or contacted by current conventional recovery practices. A significant portion of these remaining resources can be economically recovered if new, improved techniques are developed, tested, and applied that provide for delineation of their occurrence and distribution.

A focused geoscience oil and gas recovery research program can play a major role in providing cost-effective advanced technological applications required for recovery of a large component of this strategically valuable national resource. Through the application of advanced technology it is estimated that more than 90 Bbbl of oil can be added to the United States' reserves base by implementation of improved recovery practices at intermediate oil prices of $30 per barrel (fig. 1). However, even at today's lower oil prices there are significant opportunities to substantially increase reserves through advanced technological applications focused on selected components of the national oil and gas resource base.

Widespread support exists in the public sector and in industry for establishment of an integrated multidisciplinary geoscience oil and gas recovery research program. In the FY87 Continuing Resolution, Congress appropriated funding to support a program study to identify program needs and priorities required to initiate an advanced geoscience oil and gas recovery research effort. In February 1988, based on discussions with Assistant Secretary for Fossil Energy J. A. Wampler, the Geoscience Institute for Oil and Gas Recovery Research developed a plan to undertake such a study for the Department of Energy.

The Geoscience Institute, a consortium of leading national universities and state research agencies with established advanced oil and gas recovery research capabilities, initiated the program study in May 1988. From the beginning there was a commitment to incorporating a broad, multidisciplinary, technical base into the program study effort. More than 500 engineers, geophysicists, and geologists, representing industry, state, and federal research agencies and universities, participated in various phases of this study. This collaborative effort provided the basis for development of a comprehensive study that outlines the regional and national program priorities required for a focused, multidisciplinary oil and gas recovery research effort.

The Geoscience Institute's program study report is summarized in three volumes. This volume is the Program Study Summary Report, which contains recommendations for program options and descriptions of the highest priority research activities. The Technical Subcommittees Program Reports (Geoscience Institute, 1988b) provide detailed descriptions of individual research activities related to the study's six major program elements. Summary reports from a series of Regional Technical Forums, hosted by the Institute (1988c) focus on technology needs related to specific hydrocarbon provinces. These reports document and comprise the broadest based oil and gas recovery program study recommendations developed in the public sector.

Recovery Research Funding

According to a survey of 20 public-sector research universities and state agencies with advanced oil and gas recovery programs, their annual oil and gas recovery research funding level is more than $38 million. Research programs are primarily supported by state alloca-

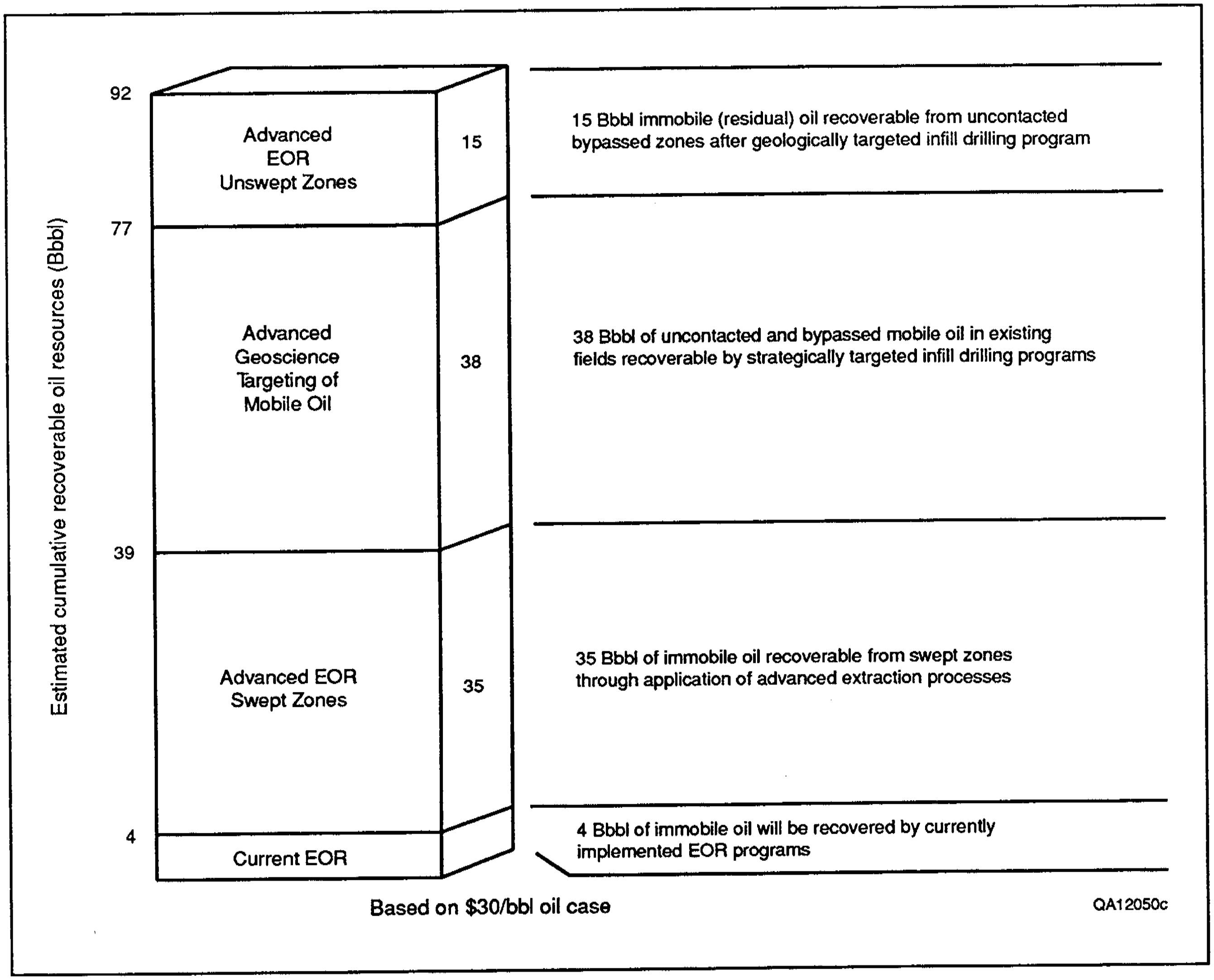

FIGURE 1. Estimated additional recovery of target mobile and immobile oil from existing fields. After NPC (1984), Fisher (1988), and ICF-Lewin (unpublished).

tions (35 percent) and industry grants and contracts (31 percent). Federal government funding, primarily through the Department of Energy (DOE), accounts for 16 percent of the current program effort. Individual university funding, Gas Research Institute (GRI) grants, and other research agency contributions supply the remaining 18 percent.

A match-fund component in the proposed DOE geoscience oil and gas recovery research effort would facilitate participation of those organizations with established advanced recovery programs. It would also encourage industry and states to join the program to gain the benefits of highly leveraged, cost-shared research. According to the Institute's study, more than $30 million of new nonfederal funds are annually available for program-matching purposes. A comprehensive, cost-shared research program can provide new, cost-effective advanced technologies for improved recovery efficiencies in a timely fashion.

Major Program Elements

The Geoscience Institute's program study is focused on recovery research, not exploration, and is aimed at improved understanding of controls on reservoir heterogeneities and development of technology that will provide improved recovery efficiency of oil and gas resources in existing reservoirs. The primary technical areas recommended for program development are the six major technical program elements, defined by the Institute's Technical Study Committee, outlined below:

(1) Field Reservoir Frameworks
The occurrence and distribution of reservoirs and their intrafield variability are controlled by stratigraphic and structural frameworks. Targeting outpost and development wells to extend field limits, test undrained fault segments, and evaluate deeper pool potential requires interpretation of the stratigraphic and structural framework of the field. Field framework studies also provide the basis for detailed reservoir characterization.

(2) Reservoir Characterization
Understanding reservoir heterogeneity in terms of reservoir genesis and its control on the distribution of hydrocarbon saturation and fluid flow characteristics is critical for efficient recovery of oil and gas. Reservoir characterization studies provide the basic input required for targeting infill wells, designing advanced extraction programs, and developing simulation models to predict and analyze production performance.

(3) Reservoir Performance Prediction
Prediction of reservoir performance using simulation models provides the key methodology for evaluation of proposed advanced recovery programs. Only through improved quantified interwell descriptions of flow units, made possible through more rigorous reservoir characterizations, can improved computer programs be developed that provide for advanced reservoir performance predictive models.

(4) Advanced Extraction Technology
The capillarity, mobility, and miscibility of reservoir fluids are critical properties that control the efficiency of recovery processes. Use of surfactants and solvents can drastically reduce capillary forces and provide for improved recovery of immobile (residual) oil. Development of mobility control agents to reduce the effect of reservoir heterogeneity on fluid flow provides improved sweep efficiency for recovery of bypassed mobile and immobile oil.

(5) Stimulation and Completion Technology
Unswept oil and gas in low-permeability zones is a significant target for additional recovery. Delineating and contacting these bypassed pay zones require improved formation evaluation, well completion techniques, and stimulation methods.

(6) Resource Assessment, Data Bases, and Technology Transfer
The characteristics, geologic occurrence, and geographic distribution of the oil and gas resources in existing fields need to be documented in a standard format on a national basis. Development of such a data base will allow regional prioritization and selection of areas for technology deployment and research emphasis.

The success of the advanced geoscience research initiative will depend on how well and how quickly new understandings, concepts, and technological developments can be transferred to the operators and service companies. Efficient technology transfer requires providing effective publications and establishing special seminars and workshops and continuing education courses in joint cooperative programs with industry. Newly hired graduates from universities participating in the new geoscience research initiative provide an essential technology transfer element.

Prioritization of Research Activities

Working jointly with the Technical Subcommittees, the Institute's Technical Study Committee identified the high-priority research activities for program consideration. Based on the Regional Technical Forum reports, the subcommittees recommended and identified research activities for each of the major technical program elements. They identified 166 research activities and 289 example projects for program consideration (table 1). Inclusion of all 166 activities identified by the subcommittees in the program is estimated to require an annual support level of $125 million.

In order to develop optional program opportunities at reduced funding levels, the subcommittees individually prioritized research activities by program elements into Priority–1,

Table 1. **Technical Subcommittees program study summary.**

Major program element	Research areas	Research activities	Example projects
Field reservoir frameworks	7	31	44
Reservoir characterization	5	27	74
Reservoir performance prediction	7	22	45
Advanced extraction technology	6	28	66
Stimulation and completion technology	12	45	42
Resource assessment, data bases, and technology transfer	4	13	18
TOTAL	**41**	**166**	**289**

Table 2. **Highest ranked Priority-1 research activities force-ranked across program elements.**

Rank	Program Element*	Objective
1	RAT	• Establish effective technology transfer system
2	RPP	• Improve averaging procedures for reservoir simulation
3	RC	• Identify controls of geologic heterogeneity on reservoir performance
4	RC	• Initiate reservoir-scale outcrop investigations
5	FRF	• Improve 3-D high-resolution mapping
6	RC	• Develop improved methods for integrating numerical and semiquantitative data
7	RC	• Develop a national assessment of unrecovered oil and gas resources
8	RC	• Improve geophysical methods for characterizing fractures
9	FRF	• Improve 4-D stratigraphic sequence models
10	FRF	• Test multicomponent seismic data for lithology and fluid prediction
11	SCT	• Develop methods to measure hydrocarbon/water saturations behind pipe
12	AET	• Improve methods for mobility control
13	RPP	• Improve modeling of basic fluid flow in heterogeneous systems
14	RPP	• Test application of physical models (CT scanning) for simulator verification
15	RC	• Develop rapid cost-effective methods for reservoir heterogeneity description
16	FRF	• Improve rock mechanics and in situ stress characterization for fracture prediction
17	SCT	• Develop improved evaluation methods for horizontal wells
18	AET	• Enhance near-well profile control and permeability modification
19	FRF	• Develop structural style models for reservoir frameworks
20	RPP	• Develop low-cost performance prediction methods
21	FRF	• Develop forward process-response geological models
22	SCT	• Enhance methods for simulation and modeling of hydraulic fracturing
23	SCT	• Enhance modeling of multiphase flow and inflow performance
24	SCT	• Develop improved cement bond logging techniques

*FRF: Field Reservoir Frameworks; RC: Reservoir Characterization; RPP: Reservoir Performance Prediction; AET: Advanced Extraction Technology; SCT: Stimulation and Completion Technology; RAT: Resource Assessment, Data Bases, and Technology Transfer

Priority-2, and Priority-3 categories. They identified 64 Priority-1, 60 Priority-2, and 40 Priority-3 activities. The Technical Study Committee in conjunction with the subcommittee cochairmen further prioritized the 64 Priority-1 research activities and force-ranked the top 24 highest priority activities across program elements (table 2). To eliminate overlap and redundancies within the Priority-1 category, certain activities were combined; this recombination resulted in the identification of 51 individual Priority-1 research activities.

Within this prioritization, 13 of the 24 top-ranked research activities focus on the reservoir heterogeneity program. Improved methods for (1) characterizing reservoirs for strategically targeted infill drilling and (2) quantifying heterogeneity descriptions for use in simulation modeling and advanced extraction process evaluation are the two most critical, highest priority program needs. Four of the top-ranked activities identify research needs for improved methods to evaluate the control of structural compartmentalization and fracture characteristics on reservoir productivity. The committee also identified development of a national field data base of unrecovered oil and gas resources and establishment of an effective technology transfer program as high-priority activities.

Multidisciplinary Program Options

To identify opportunities for integrated program options, all 51 Priority-1 research activities were grouped into one of three key multidisciplinary categories or were listed within an individual-discipline category, as outlined below.

(1) Reservoir Heterogeneity
The reservoir heterogeneity research activities were the highest ranked and were judged to constitute the most critical program needs for the new advanced recovery program. This category includes development of improved methods for (a) mapping and modeling heterogeneities, (b) scaling reservoir properties, and (c) testing advanced mobility control agents. Methods for refining quantification of reservoir descriptions for simulation performance prediction are also included in this category.

(2) Reservoir Geomechanics
The reservoir geomechanics category includes research activities that focus on developing methods of characterizing fractured reservoirs, enhancing understanding of the structural controls on hydrocarbon distribution and fluid flow, improving induced-fracture well treatments, and devising better methods for predicting performance of fractured reservoirs.

(3) Rock/Fluid Interactions
This category includes research activities focused on interaction of natural as well as injected fluids on reservoir rock properties and performance. Improved understanding of mineral equilibria and kinetics of reactions at in situ reservoir conditions is required for development of modeling techniques for prediction of reservoir quality and recovery efficiency.

Based on prioritization and categorization of Priority-1 research activities, three multidisciplinary program options at $10 million, $20 million, and $50 million levels were developed (table 3). The primary thrust of the $10 million program is an integrated reservoir heterogeneity effort. This program comprises 11 highest ranked activities related to delineating and mapping reservoir heterogeneities, defining and reducing the effect of heterogeneity on extraction processes, and developing methods for improved quantification and scaling of heterogeneity data for reservoir simulation, performance prediction, and design of development programs.

The $20 million program includes the $10 million program and an additional 13 research activities. This program option includes all 24 highest ranked, Priority-1 research activities (table 2), which are grouped into reservoir heterogeneity and reservoir geomechanics programs. In addition to the emphasis on heterogeneity, the program focuses on structural controls on reservoir producibility as well as five individual-discipline-oriented research activities.

The $50 million program includes all 51 Priority-1 research activities. It comprises additional reservoir heterogeneity and reservoir geomechanics activities as well as a new rock/fluid interaction program. In addition, 10 of the high-priority, individual-discipline activities are included in the $50 million program.

Table 3. **Summary of program areas, option levels, and research activities.**

Program Areas	Program Option Level Number of Research Activities		
	$10 Million	**$20 Million**	**$50 Million**
Reservoir heterogeneity	9	13	19
Reservoir geomechanics	—	4	10
Rock/fluid interactions	—	—	5
Singular discipline	2	7	17
TOTAL RESEARCH ACTIVITIES	**11**	**24**	**51**

Multidisciplinary Geoscience Research Programs

Joint industry and public-sector consortia constitute an excellent mechanism for conducting focused, nationally based, multidisciplinary oil and gas recovery research. Until recently, funding for multidisciplinary programs has not had widespread support. However, DOE's new geoscience initiative with joint industry participation provides additional important new opportunities for such program efforts.

A new DOE program initiative including organizations with well-established, recognized oil and gas recovery programs would provide coordination among engineers, geophysicists, and geologists and would help develop the disciplinary synergism required for significant new technological breakthroughs. Jointly funded programs supported by industry, state appropriations, and DOE provide an excellent opportunity for development of a highly leveraged, cost-shared oil and gas recovery research initiative. These objectives can best be achieved by public-sector consortia with well-established, widely recognized oil and gas recovery programs. The new program initiative will succeed only if integrated, well-focused, interdisciplinary research proposals are developed.

Furthermore, opportunities must be identified to encourage broad industry participation on a project-by-project basis. Industry can play a key role in providing technical guidance and assessment. Industry can also supply matching funds for programs. Public-sector consortia with well-established, widely recognized oil and gas recovery programs can make a significant contribution to the attainment of these objectives.

Lastly, the final requirement for a successful multidisciplinary geoscience program is the establishment of effective technology transfer. Review of research results between program participants and industry is critical. Formal exchanges through reports, seminars, and short courses are required to promote/heighten communication between industry and research consortia. Such opportunities to discuss program results and transfer technology to industry will ensure proper integration of the research effort.

Introduction and Background

The decline in oil prices and subsequent reductions in oil and gas exploration and development activities over the past 2 years have severely impacted the domestic oil and gas industry of the United States. Exploration and field development budgets have been slashed and research activities significantly reduced to accommodate projected lower prices. Major companies have reduced their technical staffs by an average of 25 to 30 percent, and many smaller companies and independents are no longer operating. Mergers of several major companies in the last few years have compounded the overall decline in industry activity. The domestic oil and gas industry has undergone a major retrenchment, which has resulted in the largest drop in the nation's oil production in history, and production declines are still continuing. As predicted, imports of foreign oil have increased during the past 2 years, reaching 40 percent in 1988, and at the current rate are projected to reach 50 percent by the early 1990's.

These trends can be modified and possibly reversed if the U.S. government develops and adopts prudent energy policies that include favorable economic incentives for new production and funding for development of new advanced recovery technology. Science and technology have a major role to play in lessening the nation's dependency on foreign oil by providing new understanding, tools, and methodology for improving recovery efficiencies.

Recent evaluations of the U.S. oil and gas resource base show that a new, focused, comprehensive recovery research program can help increase domestic U.S. oil and gas production (Fisher, 1988). There is an enormous resource potential in existing U.S. oil fields that requires new understanding of reservoir heterogeneity and development of improved technological approaches for recovery. Although more than 300 billion barrels of unrecovered oil resources remain in already discovered fields, most of these resources are unprofitable to develop at lower oil prices using existing technology. However, with improved scientific understanding of oil and gas reservoirs combined with new technological applications, a large share of this resource base can be delineated, contacted, and added to the U.S. reserves base at moderate oil prices of $20 to $30 per barrel.

Supporting Background Studies

Concern over the United States' energy dilemma and related national security has led to several important new studies that highlight the need for reduced dependence on foreign oil. This goal can, in part, be accomplished through integrated, multidisciplinary research that will provide improved methods and techniques to delineate and produce mobile and immobile oil and to locate and extract untapped gas in existing reservoirs. This current report is in response to, and complements a number of, prior Department of Energy (DOE) studies related to the nation's oil and gas recovery research needs.

Taken collectively, these previous works suggest that needs and opportunities exist for an increased public-sector role in conducting highly focused oil and gas recovery research programs. Although prior studies have had slightly differing emphases, most call for establishing a new, multidisciplinary, geoscience program approach with a focus on oil and gas recovery research that would include petroleum engineers, geologists, and geophysicists. The studies suggest opportunities for appropriate interfaces between various public-sector programs, industry groups, and DOE activities in joint support of such a new research initiative. Most of the studies recognize that strong industry participation and guidance is required for success of a new public-sector oil and gas recovery research initiative.

Several recent studies and key recommendations concerning a new, comprehensive, public-sector oil and gas recovery research initiative are summarized below.

- The Energy Research Advisory Board's (ERAB) report, *Geoscience Research for Energy Security* (February 1987) states, "A shortage of domestic liquid hydrocarbon fuels . . . threatens the nation's energy security and international competitiveness." The report recommends establishing a new geoscience oil and gas research initiative focused on methods for increasing the nation's domestic production. The report suggests that an initial annual funding level of $50 million would be an appropriate level of support for the new initiative.

- The National Research Council's (NRC) report, *Future Directions in Advanced Exploratory Research* (1987) states, "The efficient detection, recovery, and processing of domestic oil and gas resources are of critical importance to a national strategy of preparedness for a future of uncertain supplies and prices for liquid fossil fuels" and recommends support of DOE's new ERAB geoscience research initiative proposal.
- The Department of Energy's report, *Geoscience Research for Oil and Gas Discovery and Recovery* (March 1987), concludes that "advances in the oil and gas geosciences could significantly expand the amount of domestic petroleum that could be recovered at moderate costs."
- The Department of Energy's report to the President on *Energy Security* (March 1987) discusses the critical issues related to oil supply and supports the need for advanced petroleum recovery technology to halt the decline in domestic production.
- The Department of Energy's sponsored report, *Research Needs for Hydrocarbon Fuels*, prepared by the Houston Area Research Council (HARC) (May 1987), emphasizes the need for a new multidisciplinary oil and gas recovery research effort that would include geologists, geophysicists, geochemists, and petroleum engineers to address declining domestic oil production in the United States.
- The National Petroleum Council's (NPC) report on *Integrating R&D Efforts* (June 1988) recommends that "An industry forum should be established to facilitate industry support for cooperative projects aimed at improving ultimate oil recovery . . ." and "Support for multidisciplinary research in universities should be encouraged with modest funding increases in selected areas."
- The Department of Energy's report, *EOR Initiative—A Strategy for Enhanced Domestic Oil Production* (August 1988), recommends broadening DOE's Fossil Energy program to include near-term (1 to 2 years) objectives focused on improved recovery. It identifies and recommends research thrusts to improve production from existing oil fields.
- An article by W. L. Fisher, titled "Can the U.S. Oil and Gas Resource Base Support Sustained Production?" (*Science*, June 26, 1987), suggests that, with improved geologically targeted development drilling and advanced tertiary recovery techniques, the U.S. oil resource base can provide stable production in the Lower-48 states for at least the next 50 years.
- In a Bureau of Economic Geology Report of Investigations prepared for the Department of Energy by R. J. Finley and others (1988), the Gas Assessment Review Panel estimated that the United States' extended gas reserve growth potential was 119 Tcf. They recognized that the "more heterogeneous reservoirs have lower estimated ultimate recoveries (EUR) measured by standard methods and therefore have more potential for reserve growth" with application of advanced recovery techniques.

These and other recent reports and studies demonstrate widespread support for an advanced geoscience oil and gas recovery research effort in the public sector. For the most part, these studies recommend that this initiative be multidisciplinary, should focus on near-term applied recovery needs, and should involve joint support and coordination of industry, universities/state agencies, and the Department of Energy.

New Geoscience Research Initiative

Historically, the Department of Energy's Office of Fossil Energy oil and gas recovery program has focused on longer term, higher risk energy research projects that supported and complemented research in private industry. With the decline in oil prices and resulting decrease in production, current consensus as outlined above suggests opportunities for redirecting DOE's oil and gas recovery research program with joint university and industry participation.

To coordinate DOE's geoscience fossil energy research programs, the Office of Fossil Energy established the Hydrocarbon Geoscience Research Coordinating Committee and the Office of Geoscience Research. In addition, DOE's Office of Fossil Energy requested the Geoscience Institute for Oil and Gas Recovery Research to undertake a study of key programs and research activities required to initiate a new integrated research effort focused on improved recovery of existing oil and gas resources in already discovered fields.

More specifically, the Office of Fossil Energy requested the Geoscience Institute to undertake the study to identify the major technical program elements, research activities, priorities, timing, and costs required to initiate a comprehensive, multidisciplinary, geoscience oil and gas recovery research program. Emphasis of this study is therefore on recovery research needs and opportunities, not on exploration.

The major goal of the study is to identify program priorities required for development of new concepts, advanced reservoir models, and technology to maximize recovery of mobile and immobile oil and natural gas resources from existing fields. Following the Energy Research Advisory Board's (ERAB) Solid Earth Sciences Panel recommendation, a major target of the study is shorter term, lower risk research opportunities for improving recovery efficiency. However, the study also evaluates and identifies longer term, more fundamental recovery research options. The study provides a synthesis and prioritization of research activities across major discipline program elements to identify the most important and critical needs for a new, integrated recovery research program.

This study also outlines a strategy for integrating the major technical program elements to better coordinate reservoir geology, petroleum engineering, and development geophysics aspects of oil and gas recovery research. Such coordination is necessary because one of the major causes of program failures, when transferring recovery research projects from the laboratory to the field-test stage, results from too narrow a disciplinary approach. A more integrated, multidisciplinary base allows for a synergistic, problem-oriented program for improved recovery efficiencies.

Results are summarized in three volumes. This volume, the Recommendations and Program Study Summary Report, contains the key program recommendations and a description of the highest priority research activities. The Technical Subcommittees Program Summary (Geoscience Institute, 1988b) covers six major program elements and includes a comprehensive description of all related research activities. Summary reports from six Regional Technical Forums that focused on technology needs related to specific hydrocarbon provinces are presented in Geoscience Institute (1988c).

Incentives for Oil and Gas Recovery Research Initiative

Although only 5 percent of the world's population resides within its borders, the United States consumes 24 percent of the world's total energy supply (EIA, 1987a). Our per capita energy consumption of 53 barrels of oil equivalent (BOE) per year is the highest in the world (EIA, 1987a). Despite this enormous energy consumption, the only real near-term energy shortfall facing the nation, in terms of domestic production, is that of liquid fuels, used primarily for transportation and industrial applications. For most types of energy demand, notably heating and electricity production, the U.S. is largely self-sufficient, because of enormous domestic supplies of coal, with assists from natural gas, nuclear, hydroelectric, and geothermal supplies. However, in the area of transportation, which is almost totally dependent on crude oil, the U.S. must turn to outside supplies to satisfy domestic demand.

In comparison to its demand for crude oil, the United States produces only 15 percent of the world's oil (API, 1988a), while holding claim to only 4 percent of world's proved reserves (API, 1988b). Meanwhile, no immediately acceptable fuel substitute is available to replace crude oil, and there is no indication that oil demand will diminish. Therefore, to reduce the national reliance upon foreign sources of crude oil in the near term, emphasis must be placed on improving recovery efficiencies in order to extract a greater percentage of remaining hydrocarbon resources from existing fields within the United States.

National Energy Issues

More than 3 million holes have been drilled in the search for oil and natural gas in the United States, whereas only about 750,000 have been drilled throughout the rest of the world. Currently, the U.S. drills 64 percent of all the wells in the world (*World Oil*, 1988) and has more than 600,000 wells in operation, each averaging 13 barrels of oil per day (BOPD) (fig. 2). This compares to an average throughout the rest of the world of 250 BOPD per well.

Despite concentrated efforts to maintain domestic production levels, both production and proved reserves are in decline. Domestic production of crude oil in the Lower 48 states peaked in 1970 at 9.4 million BOPD and began to fall steadily until the early 1980's, when a short-lived period of higher world oil prices resulted in increased drilling and helped maintain domestic production. By 1987, with the decrease in oil prices, production had dropped to less than 7 million BOPD. Proved reserves in the Lower 48 states, meanwhile, peaked in 1961 at 32 billion barrels, began to decline, and was at 27 billion barrels in 1987 (EIA, 1987b). The addition of substantial reserves and production from the Prudhoe Bay discovery in Alaska has helped the U.S. maintain production, but now production from this field has peaked and is expected to decline in 1989. Only this nation's remarkable, highly developed industrial technology base has allowed continued profitable production of oil from aging fields and continued discovery of new oil reserves in mature, heavily explored areas. This technical dominance must be maintained and improved if the U.S. hopes to continue this demonstrated success.

The nature of the United States' role in the world oil market, together with its rapidly maturing oil and gas resource base, has led to an increased reliance on imported oil. The U.S. has a long history of importing foreign oil to offset the shortfall between demand and declining domestic supply. From a 23 percent dependence on foreign oil in 1970, the U.S. increased its use of foreign supplies to a peak of 48 percent in 1977. The higher prices that followed in the mid- to late 1970's and the early 1980's had the dual impact of reducing demand and stimulating domestic production, thus reducing domestic demand for foreign oil. Just as high prices decreased demand for foreign oil, so have the low prices since 1986, predictably, increased demand. Currently, reliance on imports has increased to more than 40 percent of demand and is projected to exceed 50 percent by the early 1990's. This sustained level of crude oil imports has directly increased the United States' negative trade balance.

The vast bulk of the free world's oil imports is expected to come from the Middle East. Because

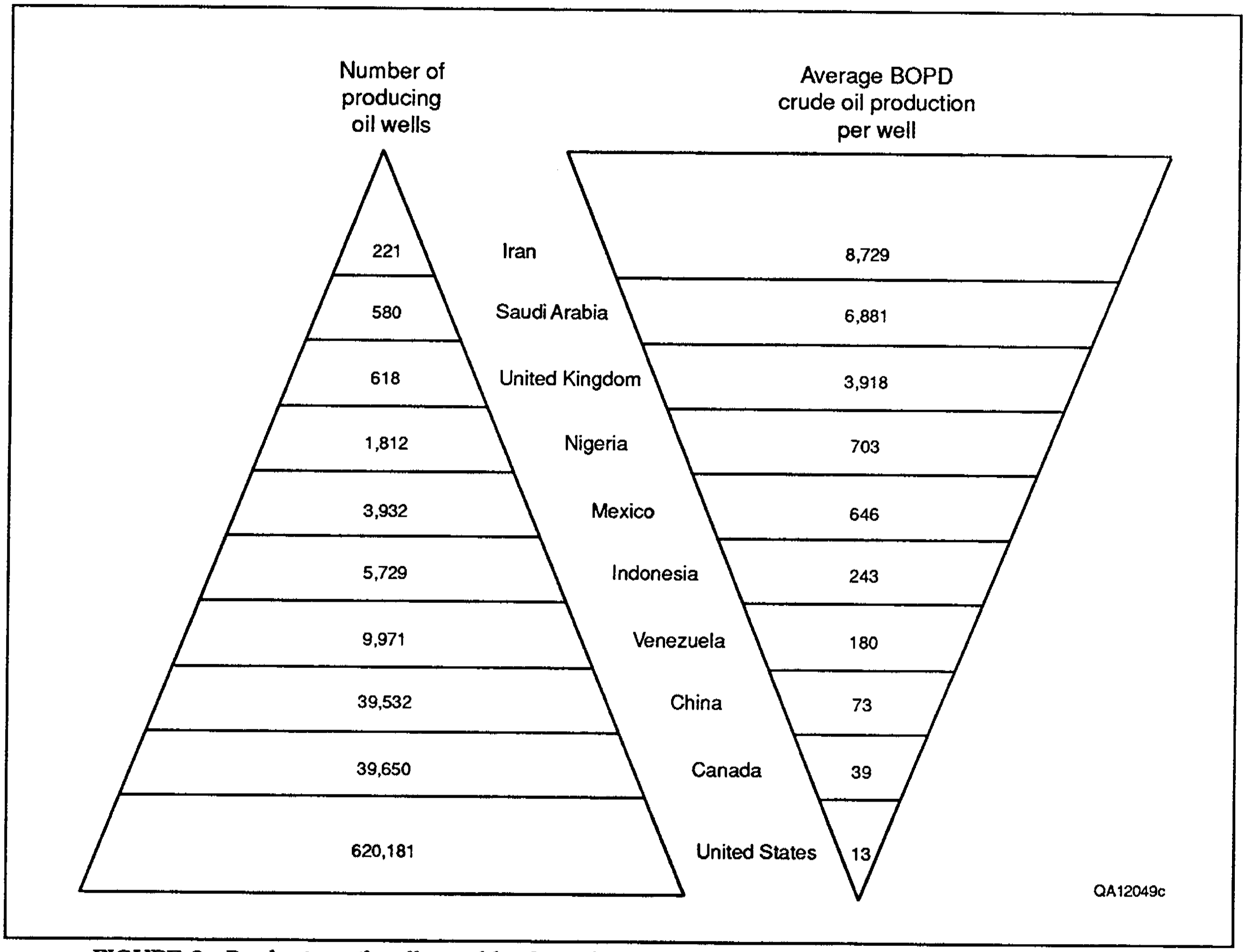

FIGURE 2. Producing oil wells worldwide and average production rates (average BOPD per well).

this is a notably unstable region, it is widely agreed that the U.S. will soon be vulnerable once again to foreign supply disruptions. However, improved recovery efficiency of the remaining domestic resource base through development and application of advanced geoscientific understanding of oil and gas reservoirs can increase recovery from existing fields and can help reduce the national dependence on foreign sources for crude oil.

Benefits of Advanced Recovery Research Program

The United States' dependence on oil, its current position in the world oil market, the state of the domestic oil industry, and the enormous potential of its remaining unrecovered oil resource in existing fields all provide strong incentives for establishing an integrated, comprehensive, geoscience oil and gas research initiative. The instability of the world oil markets over the past 15 years has demonstrated the secondary nature of the United States' role as an oil producer. It has also heightened the need for U.S. oil operators to develop an improved understanding of the geoscientific nature of hydrocarbon reservoirs in order to prolong and enhance the productiveness of the domestic petroleum resource base. By pursuing this overall objective of improving domestic recovery efficiency, a properly focused, well-managed, and sufficiently financed oil and gas geoscience research program can have the following beneficial results:

- Lessening U.S. dependence on foreign supplies of crude oil by providing technology for improved oil recovery from existing domestic fields and thereby reducing national economic and political vulnerability to incidents overseas that disturb the worldwide flow and price of oil. By doing so, the U.S. can have a positive impact on stabilizing world oil prices.
- Mitigating the severe impact that worldwide shifts in oil supply and price have on the U.S. oil industry because the foreign oil market is largely driven and controlled by government cartels.
- Helping the U.S. maintain its worldwide dominance in oil industry technology by providing broad-based support for university and state agency research programs to ensure a continued supply of trained professionals to meet the needs of operating companies.
- Providing fundamental research to the major integrated oil and gas operating companies and broader based, more applied research to the nation's thousands of smaller, independent oil producers.
- Persuading operators of stripper wells to maintain limited production rather than abandoning access to oil remaining in place, based on the rationale that developing technology can substantially enhance production and reduce operating costs in mature reservoirs.

An integrated and comprehensive geosciences research program provides a highly effective approach for addressing these energy issues facing the United States. The costs to the nation of not achieving a greater understanding of the geoscientific nature of hydrocarbon reservoirs, such as costs related to severe economic shifts, national security, and environmental dangers, far exceed the investment required to establish a comprehensive, broadly supported research program. The incentives for developing such a program, therefore, are significant with regard both to the U.S. position in the current world oil market and to future prospects for meeting U.S. energy requirements.

Availability and Supply of Technical Personnel

A primary concern resulting from the current downturn in oil industry activity is the significant loss of professional scientists and engineers. The oil price collapse in 1986 not only severely impacted U.S. production capacity but also had an even more devastating effect on the availability of trained geoscientists and engineers. Hundreds of professionals who were surplused during the economic downturn of 1985–87 have permanently left the industry. Even more ominous are the drastic reductions in university undergraduate enrollment in geology, geophysics, and petroleum engineering programs across the country.

Figure 3 shows recent trends in undergraduate and graduate enrollments in petroleum engineering, geology, and geophysics in the U.S. In all disciplines, undergraduate enrollments peaked in 1981–83 and have since declined. Undergraduate enrollments in petroleum engineering have fallen by nearly a factor of 10 since 1981. Enrollments in geology are less than a third of their 1984 peak, while undergraduate enrollment in geophysics declined by nearly a factor of 2. Although graduate enrollment has not declined as severely as undergraduate enrollment, it will decline significantly in a year or two, when the supply of bachelor's-level students diminishes. Industry can expect to face critical shortages of new, entry-level petroleum engineers, geologists, and geophysicists, particularly at the advanced degree level, by 1992. Availability of new M.S. and Ph.D. graduates will not be sufficient to meet demand.

It is critical that the educational infrastructure be preserved to ensure the United States' ability to continue to provide the best trained oil and gas professionals to address the nation's energy needs. Advanced, leading-edge, university oil and gas recovery research programs draw high-quality graduate students. These students not only conduct research but also provide an extremely efficient means of technology transfer to industry once they graduate and join their new employers. In addition, doctoral recipients provide the next generation of university faculty and key industrial research personnel.

Effective oil and gas recovery research programs in universities require active participation of oil and gas companies and related service

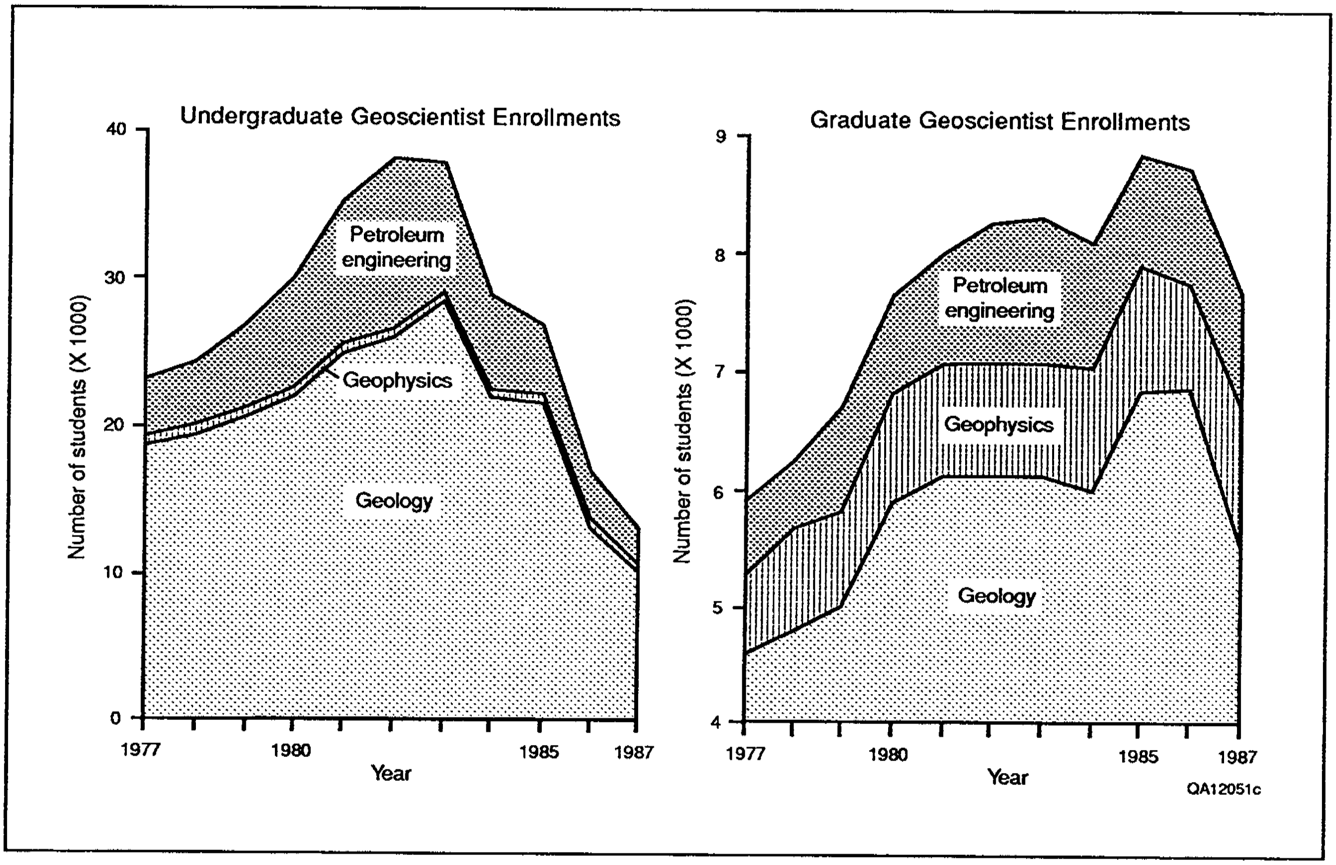

FIGURE 3. Undergraduate and graduate geoscientist enrollments in geology, geophysics, and petroleum engineering, 1977 to 1987 (American Geological Institute, 1988; Society of Petroleum Engineering, 1988).

organizations as well as other research entities. These companies provide both research funding and advice and guidance. Thus, there is a direct link between universities and operating companies that provides a rapid exchange of both research needs and research results. These organizations also rely to some extent on university faculty and related research staffs to provide on-the-job training in the form of short courses and seminars. Here too is a direct link that supplies an efficient means of transferring research results and ideas directly to industrial personnel involved with oil and gas extraction. Interdisciplinary recovery programs conducted by university faculty and state agency research staff provide continuing education programs for needed cross-training of industrial personnel.

Universities and state agencies throughout the U.S. currently have a significant personnel resource readily available to assist in the development of new and improved oil and gas recovery technology. The programs proposed by this study can mobilize and focus this personnel resource to more effectively address research needs for improved oil and gas recovery efficiency. Current petroleum engineering, geology, and geophysics faculty and researchers already have the required expertise to conduct high-quality, public-sector research. Additional research funding that becomes available for this effort can also provide baseline support to attract qualified students and thus will have a direct, near-term impact on oil and gas recovery research accomplishments. But, more importantly, funding to universities will have a significant long-term effect and will help stabilize the supply of technical professionals that will be required by industry in the future.

Resource Target Opportunities for Advanced Oil and Gas Recovery Research

Domestic Oil Resource Base

Despite the steady decline in domestic oil and gas production and reserves, an enormous resource is being left unrecovered in existing reservoirs (fig. 4). During the past century, nearly 500 Bbbl of oil has been discovered in U.S. oil fields (BPO, 1987). Of this resource, 144 Bbbl has been produced and an additional 27 Bbbl is considered to be recoverable proven reserves, given existing technology and economic conditions. However, it is estimated that, after completion of conventional recovery activities using current practices, more than 325 Bbbl, or 64 percent of the total original oil in place (OOIP) in domestic fields, will remain trapped in existing reservoirs. In addition to this oil resource, more than 460 Tcf of inferred, extended, and low-permeability natural gas resources occur in existing fields. These known U.S. oil and gas resources occur in complex, heterogeneous reservoirs that have not been uniformly contacted or swept by current recovery practices. A significant portion of these remaining resources can be economically recovered if new, improved techniques are developed, tested, and applied to permit their targeting and recovery. Evaluation and description of the unrecovered oil resource in terms of its components and location constitute the first step in determining the type of longer term research required for increasing recovery from existing fields.

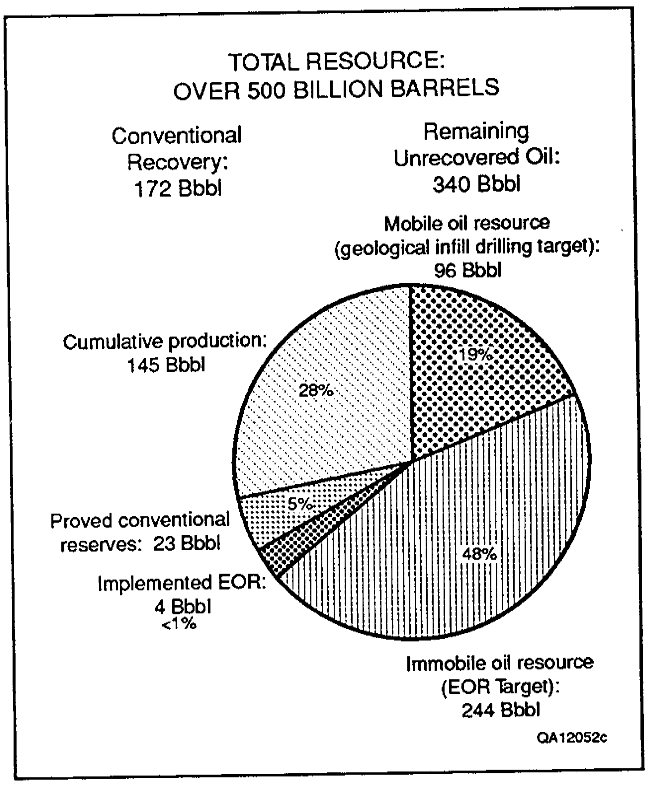

FIGURE 4. Total U.S. oil reserves and resources in existing fields—produced, proven, and remaining. After BPO/TORIS (1987).

Components of the Unrecovered Resource Base

The domestic unrecovered oil resource consists of mobile and immobile oil (fig. 4). The estimated 171 Bbbl that will ultimately be produced by current conventional recovery practices is mobile oil. However, the remaining unrecovered 325 Bbbl consists of both mobile and immobile oil components, each of which is a significant target for development of advanced recovery techniques.

The nature of the controls trapping these two classes of oil is different; therefore, the technology required to recover the oil is also different. Certain advanced recovery techniques are applicable to one component of the resource but not the other. For this reason, a detailed description of the distribution and occurrence of the oil resource components is critical in planning an advanced recovery research program.

Unrecovered mobile oil is the portion of the resource base that has not been contacted or swept during primary or secondary production; it is estimated to account for nearly 100 Bbbl of the remaining in-place resource. The vast majority of mobile oil is left in the reservoir due to reservoir heterogeneities, causing segments of the oil zone to be compartmentalized and uncontacted or bypassed and unswept by injected fluids due to permeability variations. Recovery of this oil depends on development of improved, integrated geological and geophysical interpretation methods that can effectively delineate the distribution of remaining mobile oil for implementation of targeted infill drilling and advanced recovery programs. The key to success of future mobile oil recovery programs is improved reservoir characterization studies to provide estimates of the volume and ultimately delineate and target the remaining unrecovered oil resource.

Immobile oil accounts for an estimated 229 Bbbl of the remaining unrecovered in-place oil resource base. The immobile oil resource can reside in both swept and unswept zones of the reservoir and is trapped by capillary reservoir forces. Immobile oil in the swept zone consists of residual oil in that portion of the reservoir where conventional production has already displaced the mobile oil. Recovery of the immobile oil resource in addition to improved characterization of reservoirs requires development of advanced enhanced oil recovery (EOR) techniques in conjunction with improved resource-targeted infill drilling practices.

Geographic Distribution of Remaining Oil Resources

The remaining oil resources reside in diverse reservoir settings across various hydrocarbon provinces. As outlined in figure 5, the majority of the unrecovered oil resource is confined to the most-oil-productive states—Louisiana, Oklahoma, Texas, and California. However, other states, such as Alaska, Mississippi, Illinois, New Mexico, Kansas, and Wyoming, contain significant oil resources.

Unrecovered mobile oil, totaling an estimated 96 Bbbl nationally as shown in figure 5, exceeds 1 Bbbl in each of 10 states. It constitutes as much as 35 Bbbl of the remaining resource in Texas. Reservoirs in California are estimated to contain nearly 27 Bbbl of conventionally recoverable mobile oil. Other states with significant unrecovered mobile oil resources include Louisiana (7.2 Bbbl), Oklahoma (6.2), Wyoming (3.9), New Mexico (3.3), Kansas (2.4), Alaska (2.1), Illinois (1.5), and Mississippi (1.1). This geographic diversity is complicated further by substantial geological differences among reservoir types within the geologic settings of the various hydrocarbon provinces. Recovery of a significant quantity of this resource will first require a thorough evaluation based on a detailed geological analysis of major reservoir types and trends in each region.

Ten states have more than 4 Bbbl of immobile oil resources (fig. 5b). States with the largest immobile oil resources are Texas (65 Bbbl), California (40 Bbbl), and Oklahoma (20 Bbbl). Significant immobile oil resources are also found in Alaska (17.3), Louisiana (15.2), Kansas (8.7), New Mexico (7.7), Wyoming (7.3), Pennsylvania (4.5), and Illinois (4.4). These states have an enormous immobile oil base, much of which could be recovered if advanced EOR processes can be economically applied to contact and produce the oil (NPC, 1984).

Geologic Controls on Recovery of Remaining Oil Resources

Oil recovery is largely dependent on three groups of variables: (1) basic rock properties, including lithology, permeability, and continuity, all of which are strongly controlled by reservoir genesis; (2) drive mechanism or reservoir energy, which is related to regional aquifer considerations; and (3) reservoir fluid properties, which are strongly controlled by oil type. Recent research indicates a direct relationship between reservoir genesis, drive mechanisms, and the volume of unrecovered mobile oil remaining in a reservoir after completion of a conventional recovery program (Tyler and others, 1984).

For example, a plot of genetic reservoir types versus mobile oil recovery efficiency (fig. 6) shows significant variability in recovery. Laterally continuous sandstone reservoir types, such as strandplains, barrier bars, and wave-dominated deltas, have higher recovery efficiencies than do fluvial and sand-rich submarine fans. This is primarily because, in general, shorezone deposits are better sorted and composed of more simply stratified units and have fewer permeability barriers than complexly stratified fluvial and submarine-fan deposits. In carbonate reservoirs, thick pinnacle-reef

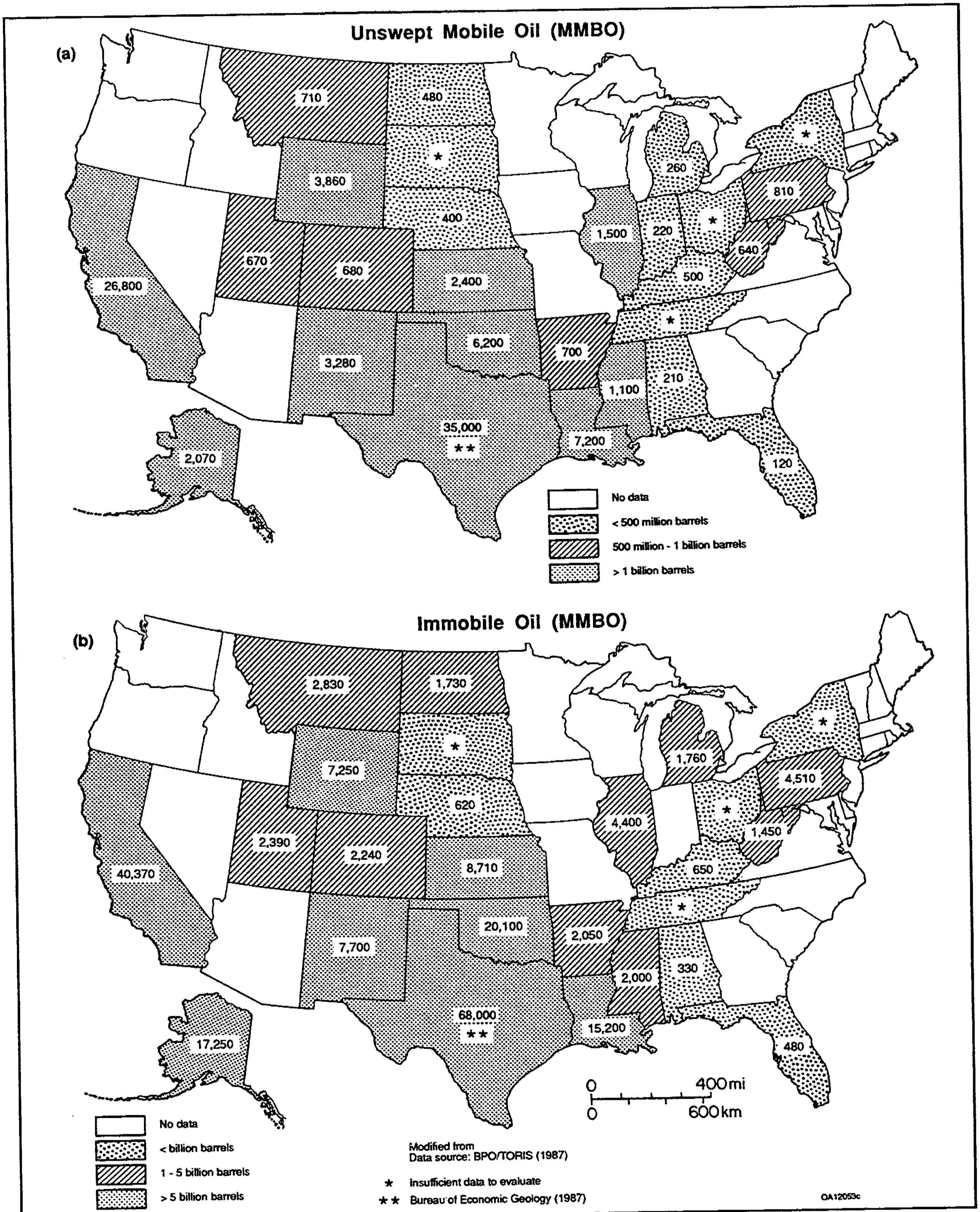

FIGURE 5. Unswept mobile oil and immobile oil resources remaining after conventional recovery. Data from BPO/TORIS (1987) and Bureau of Economic Geology (1987).

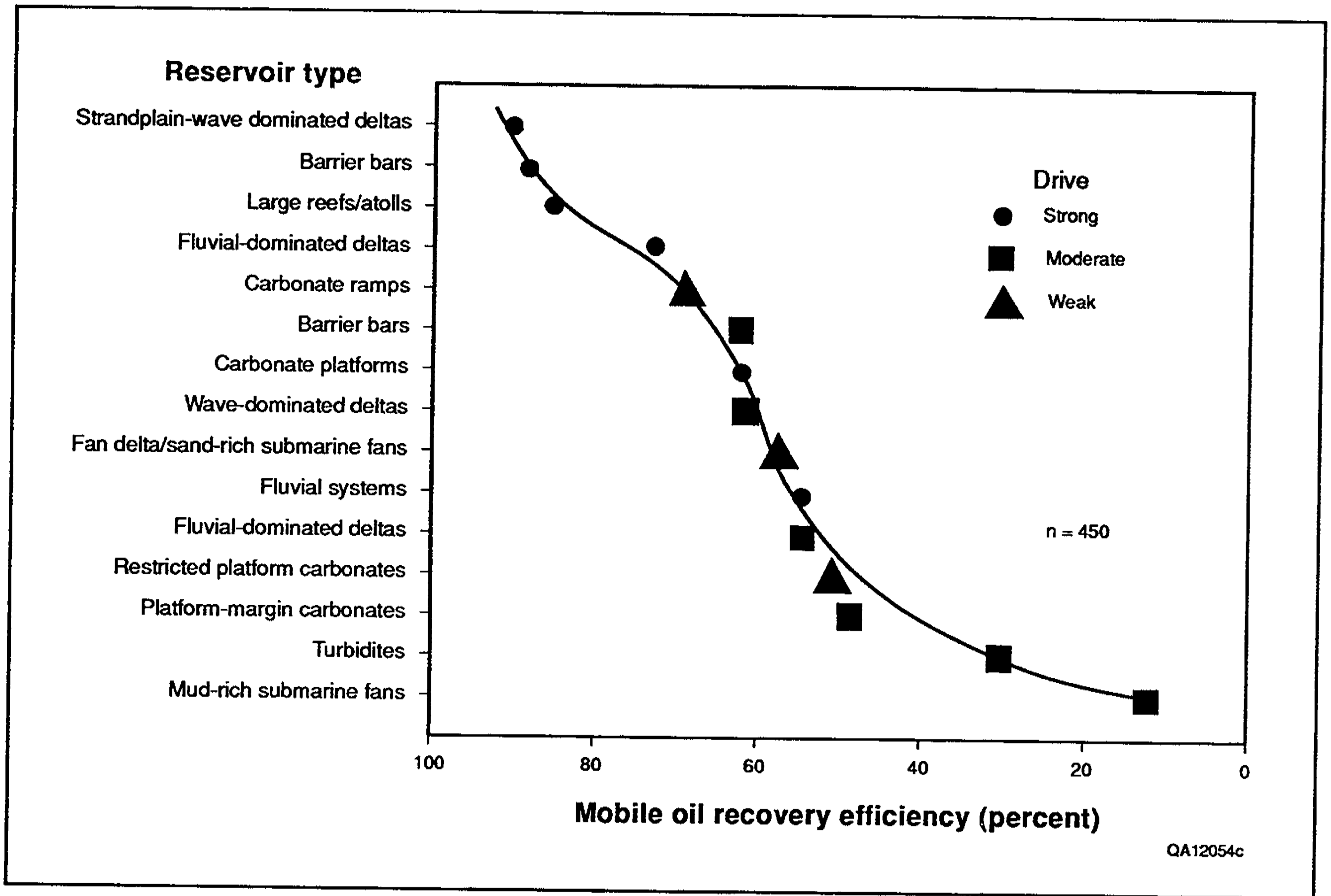

FIGURE 6. Mobile oil recovery efficiency by reservoir type. After Tyler (1988).

reservoirs commonly have excellent vertical permeability and tend to have higher recovery efficiencies than do complexly stratified restricted platform and platform-margin reservoirs, which have poor vertical permeabilities because of interbedded lime mud and sand units.

Overall average efficiency of primary and secondary recovery for all reservoirs in the U.S. is around one-third of OOIP. The two-thirds of the OOIP that remains after primary and secondary recovery exists as uncontacted and unswept mobile and immobile oil. Mobile oil remains in segregated, uncontacted compartments of the reservoir or in unswept zones bypassed by displacing fluids due to reservoir heterogeneities and injection pattern effects. Oil is bypassed because geologic heterogeneities, such as impermeable shale layers, divide the reservoir into isolated flow units unswept by injected fluids. In reservoir zones swept by secondary recovery fluids, immobile or residual oil exists that either is too viscous to be swept or is trapped by capillary forces.

Four levels of reservoir heterogeneity exist, ranging from microscopic to megascopic (fig. 7). Microscopic heterogeneity is a function of variability at the pore and pore-throat scale and is the scale of variability that governs the nature of oil saturation in a reservoir. Oil globules are trapped in pores by capillary forces, and fluid flow characteristics are controlled by the size and distribution of pore space at the microscopic scale.

Mesoscopic heterogeneity reflects variability at the lamination to bed scale. Barriers to flow, such as shale layers in sandstone reservoirs, laterally discontinuous pay beds in carbonate reservoirs, and high-permeability beds in carbonates and sandstones that act as thief zones and cycle injected fluids, all contribute to

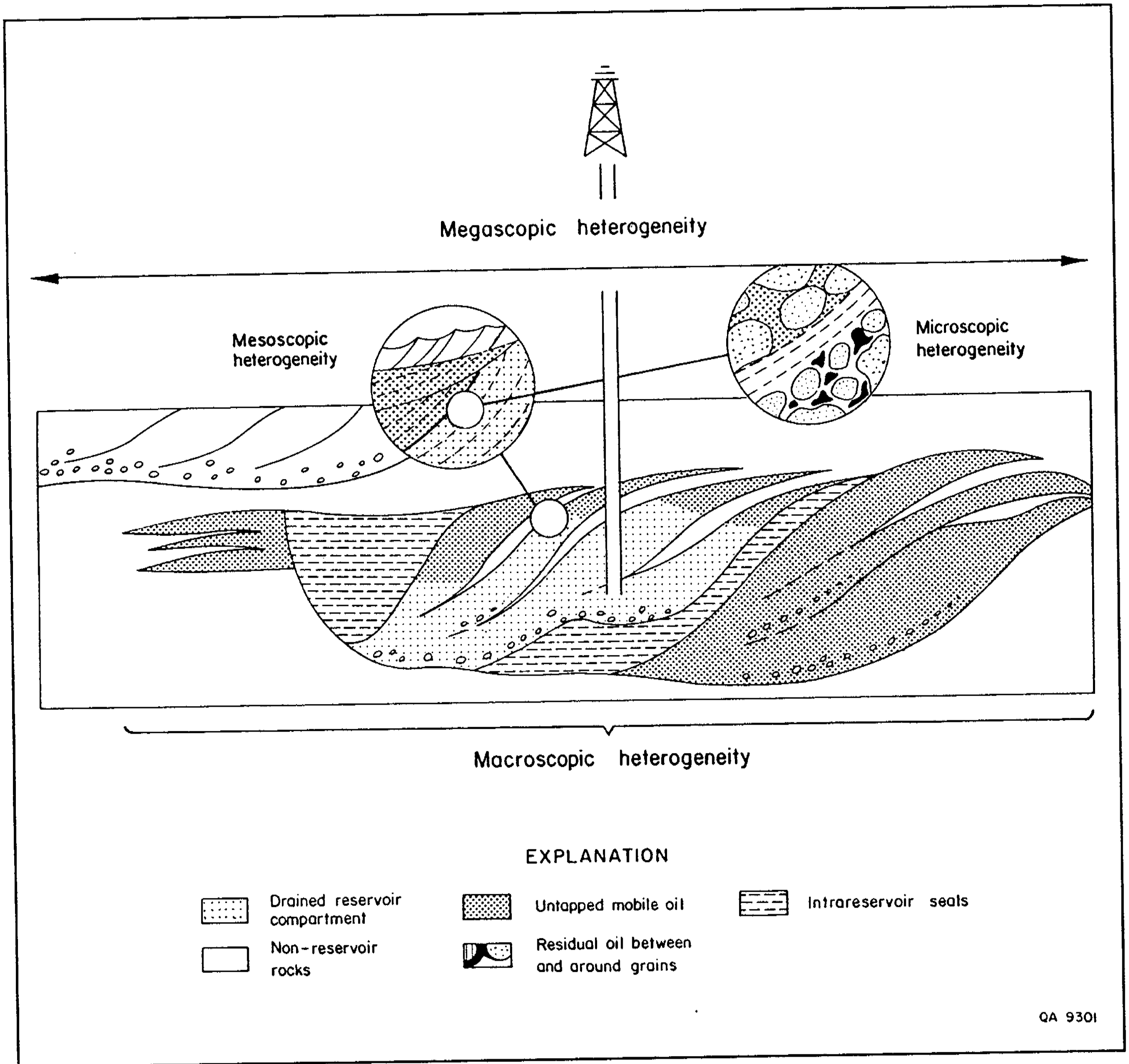

FIGURE 7. Scales of reservoir heterogeneity. After Tyler (1988).

segmenting the reservoir and cause oil zones to be uncontacted or bypassed by displacement fluids.

Macroscopic heterogeneity describes variations at the lithofacies scale. The distribution of lithofacies compartmentalizes reservoirs and controls reservoir boundaries within a field. Megascopic heterogeneity is determined by variability across depositional systems and is a major control on the distribution of reservoirs within a trend or play.

Targeted infill drilling programs designed to contact undrained reservoir compartments can significantly increase recovery efficiency. Distribution of undrained compartments is not uniform across a field, so regulatory exceptions to allow well locations to be unevenly spaced are required for targeted infill drilling programs.

Additional recovery of immobile oil and contacted, but unswept, mobile oil can result from alteration of the mobility and capillary properties of the reservoir rock and fluids. The two processes currently most in use are thermal methods in heavy oil reservoirs and carbon dioxide flooding in light oil reservoirs. Although several chemical methods have been demonstrated to recover significant amounts of residual oil in laboratory core tests and field pilots, few full-scale chemical EOR projects have been initiated.

Perhaps the strongest control on the recovery efficiency from existing reservoirs is economics. Infill drilling to contact unswept and untapped compartments, profile and mobility control measures to contact bypassed oil, and EOR processes to recover residual oil all have associated, though variable, costs. However, development of advanced recovery technology providing improved efficiencies can significantly reduce production costs.

Recovery Potential of Remaining Oil Resources

Because of economic and technical limitations, the entire domestic resource can never be recovered. However, the estimated 325 Bbbl of unrecovered oil remaining in existing reservoirs represents the overall target for advanced recovery techniques. Recent analyses have demonstrated that with improved reservoir characterization methods, better targeted infill drilling practices, and development of advanced recovery methods, recovery of large quantities of the remaining resource could be economically attractive (Fisher and Galloway, 1983; Bebout and others, 1987; Tyler and Gholston, 1988).

Development of a focused multidisciplinary research approach is the key to improving recovery efficiency. New advances in geoscientific understanding of the remaining mobile and immobile oil resource in known reservoirs and development of advanced technology can increase recovery from existing fields and could more than double current reserves at moderate oil prices. Overall program requirements to achieve such success indicate that there is a need for a coordinated research plan, including both the public and private sectors, designed to meet quantifiable recovery goals.

A coordinated geoscience research effort aimed at improving production efficiencies in the recovery of uncontacted and unswept mobile and immobile oil and untapped natural gas in existing reservoirs can provide dramatic returns at moderate costs. In 1984 the National Petroleum Council (NPC) evaluated EOR potential at various oil prices, ranging from $20 per barrel to $50 per barrel, and at two technology levels—that currently implemented and that which could be achieved by an advanced, focused recovery research and development effort. The NPC analysis included more than 2,500 individual reservoirs nationwide, describing 66 percent of the total national resource base. However, by design, the study methodology targeted only the immobile oil in the swept portions of the reservoir and did not consider the mobile oil component. At the intermediate oil price of $30 per barrel, the NPC projected that with current implemented technology nearly 15 Bbbl of remaining unrecovered oil could be economically produced from the reservoirs analyzed. This value nearly doubles to 28 Bbbl with advanced technology considerations. When the NPC recovery estimates of immobile oil are extrapolated in terms of the entire domestic oil resource base, it is estimated 39 Bbbl of immobile oil can be economically recovered from existing fields. The NPC recovery projections with more recent estimates of remaining mobile oil resources by W. L. Fisher (1988) are shown in figure 8.

Advanced geoscientifically targeted infill drilling, as opposed to uniformly spaced wells, can recover more than 40 percent of the estimated 96 Bbbl of remaining unswept mobile oil. This would add an estimated 38 Bbbl to the domestic reserves base. Estimates of recoverable EOR reserves from the unswept mobile oil zones by both current and advanced technology add another 15 Bbbl of reserves. In summary, using advanced technology, the total recoverable immobile and mobile oil reserves at $30 per barrel is estimated to be approximately 90 Bbbl (fig. 8). Although estimates of economic recovery from the recognized large unrecovered oil resource base vary widely, significant additional oil recovery can be obtained from a host of reservoir types. The potential for recovery of these resources should be sufficient to develop broad-based support for a renewed geoscientific advanced recovery research program.

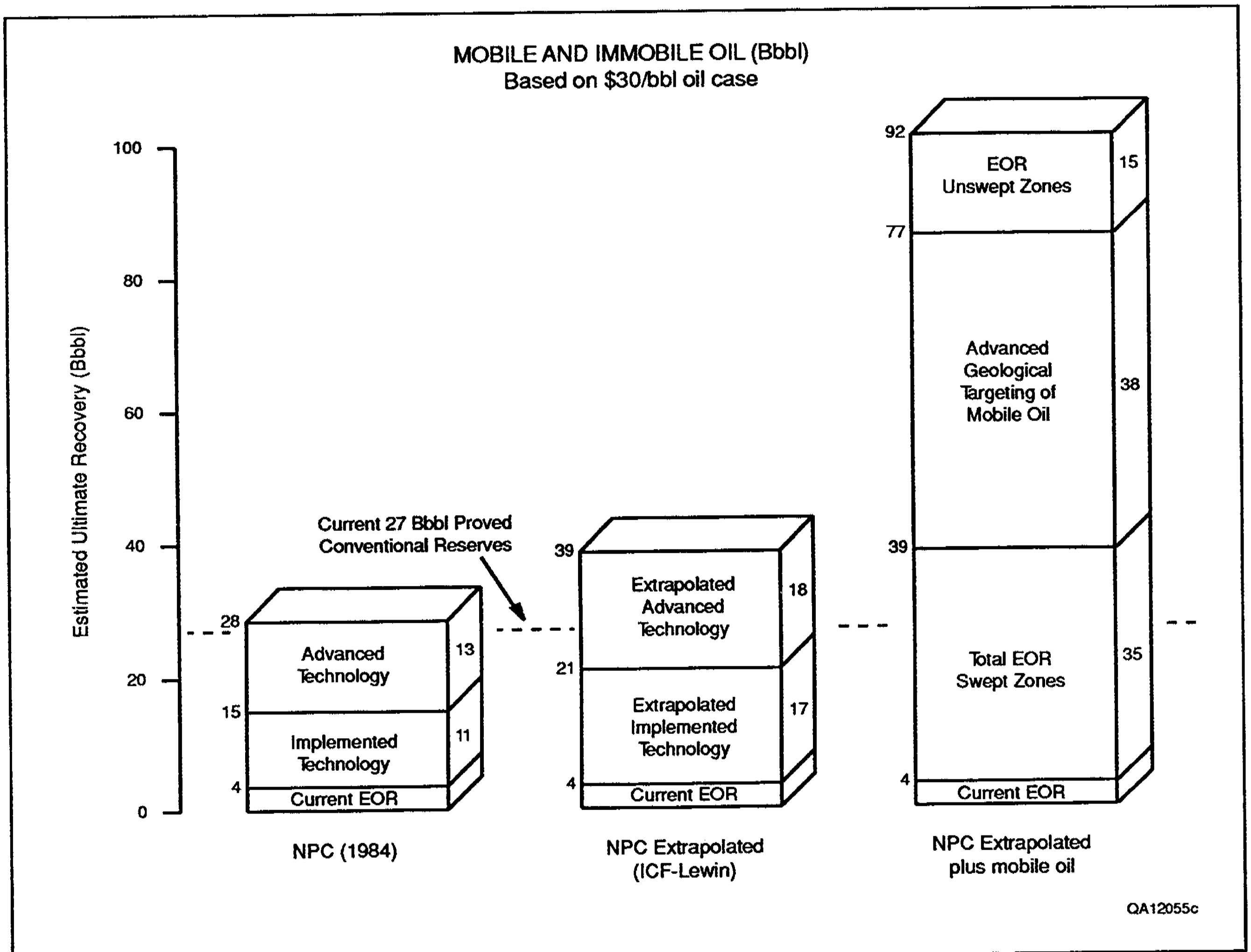

FIGURE 8. Estimated mobile and immobile oil recovery from existing fields. After NPC (1984), Fisher (1988), and ICF-Lewin (unpublished).

Successful development of improved reservoir characterization models and implementation of advanced recovery processes, currently demonstrated in the laboratory, can enhance recovery efficiency if sufficient economic incentives are available to operators for testing and employing these new technologies. Additionally, evaluation of methods to minimize the cost of initiating and maintaining EOR projects will improve project economics and increase ultimate recovery. Efforts to increase the knowledge base relative to the resource will also improve the economics by limiting operator risk and financial exposure.

Even if this substantial recovery goal (fig. 8) is achieved, more than 200 Bbbl of oil will still remain as a target for future research efforts. Future advances in evaluation techniques, characterization methods, and recovery processes could improve future, long-term oil recovery from the known resource. Achieving higher levels of recovery efficiency will require a coordinated, focused, interdisciplinary approach to solving the problems limiting current recovery and reducing the economic barriers to advanced technology. This overall program will be a challenge to implement and maintain. However, considering the massive volume of unrecovered oil trapped in domestic reservoirs, undertaking this challenge will obviously benefit both the public and private sectors and provide improved national security.

Domestic Oil and Gas Industry

Majors, Smaller Companies, and Independents

To understand the true nature of opportunities for advanced petroleum recovery research, the domestic oil industry must be viewed as a combination of two distinct entities: (1) the relatively small number of major producing companies and (2) the more than 20,000 smaller companies and independent operators. In 1986, the 16 largest major companies produced 55 percent of the oil in the U.S. and controlled 57 percent of the reserves (fig. 9). Likewise, the major companies produced 43 percent of the natural gas in the nation while holding rights to 47 percent of the proved reserves. The smaller companies and independent operators, on the other hand, accounted

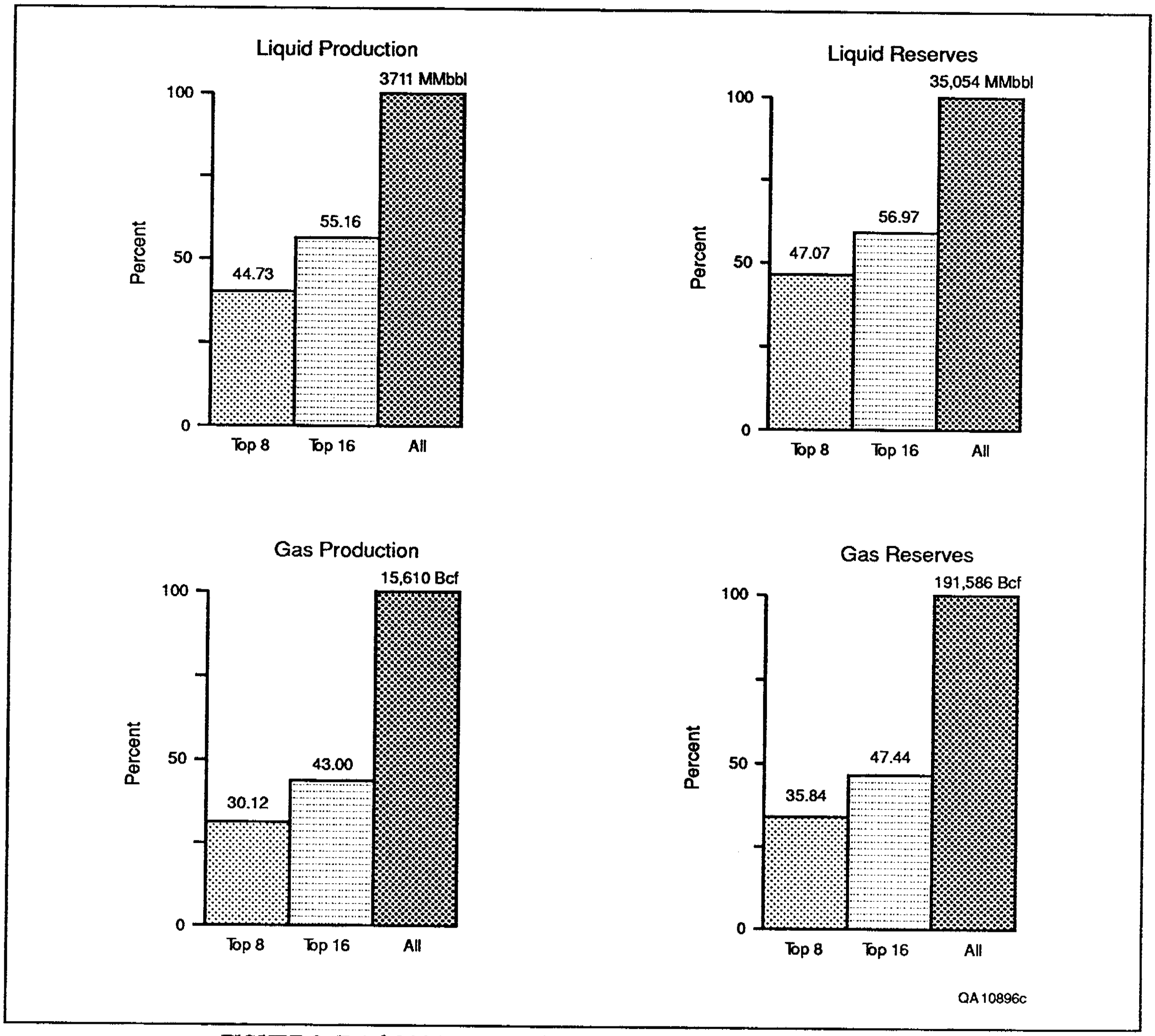

FIGURE 9. Total 1986 U.S. production and reserves by company size.

for 45 percent of the oil production and held 43 percent of the proved oil reserves. However, considering only the Lower 48 states, the smaller companies and independent operators accounted for 55 percent of the oil production and 54 percent of the proved reserves while they produced 58 percent of the natural gas and held claim to 63 percent of the proved reserves.

Oil industry response to severe fluctuations in the world oil market and depletion of our maturing domestic resource base differs markedly between the majors and the independents. The major companies have a variety of options available when responding to abrupt oil price adjustments, such as massive corporate reorganizations, shifts of investment among various operations and activities, and selection of economically appropriate international areas for exploration and production investment. The range of options available to smaller oil and gas companies and independents is far more limited. Whereas a major company might elect to pursue larger prospect opportunities overseas during periods of low oil prices, independents usually must operate onshore in the Lower 48 states, investing a relatively greater amount of money and effort while extracting less oil, and less profit, in return. These differences create research needs that are as distinctly separate as the decisions they support.

Current Industry Recovery Research and Joint Program Opportunities

In 1988, U.S. oil and gas operators and service companies spent an estimated $275 million on recovery research activities (NPC, 1988). Most of these expenditures ($209 million, or 76 percent) focused on reservoir characterization projects funded by a dozen or so major companies (fig. 10). The NPC study (1988) points out that because of the large quantity of unrecovered oil resources in existing fields and the restricted opportunities to explore in many U.S. frontier areas, it has become increasingly important to the nation and to the industry to improve recovery efficiencies from known reservoirs. According to the study,

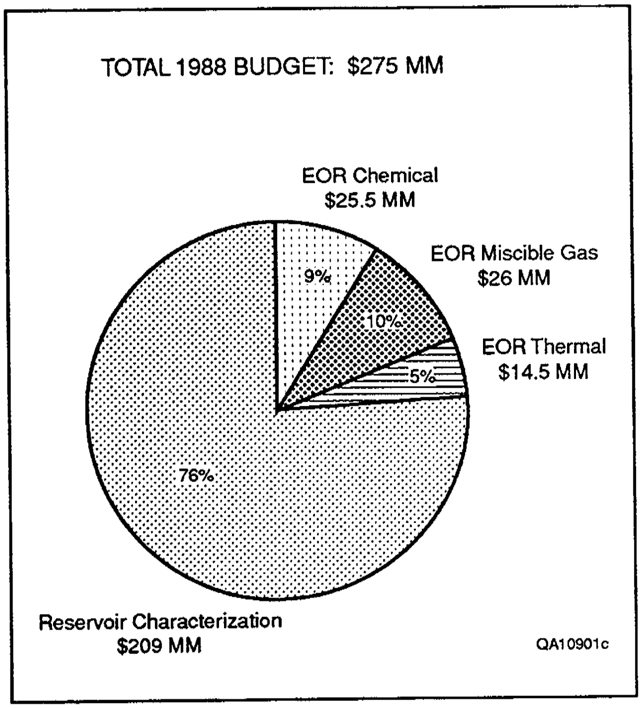

FIGURE 10. Current industry recovery research expenditures. After NPC (1988).

industry has an interest in increasing support for cooperative multidisciplinary research with universities in some specific project areas. Industry officials recognize that cooperative university research efforts will be beneficial but must balance such efforts against their stewardship responsibilities and not become dependent on outside entities for technology. Furthermore, companies with existing major research programs are unlikely to cease such efforts to enter joint projects, nor are they likely to continue such programs and simultaneously support a broad-based cooperative research program.

In regard to joint oil and gas recovery research initiatives among industry, university, and government entities, the NPC study recommends two approaches:

- First, an industry forum should be established to facilitate increased industry support for cooperative projects aimed at improving ultimate oil recovery.

- Second, support for multidisciplinary university research should be encouraged by providing modest funding increases for selected projects.

The proposed industry forum and the multidisciplinary university research projects are seen as complementary. It is suggested that synergy would develop between the two activities, the forum providing a vehicle for universities to seek industry funding for multidisciplinary projects and for industry to have improved access to existing research in academia.

In addition, the NPC study recognizes that the recent emphasis on integrated multidisciplinary geoscience research is "largely outside the purview of traditional funding sources." Industry provides some support for such multidisciplinary efforts. NPC suggests there would be potential benefit from a greater focusing of the effort with additional funding support from government and industry. The report outlines the following five key recommendations related to opportunities for expanding joint industry, university, and DOE recovery research (NPC, 1988):

- Multidisciplinary research should be encouraged to most effectively leverage advances in the areas of geology, geophysics, engineering, and related sciences.

- Research should emphasize development of methodologies to improve the ability to characterize complex reservoirs in the subsurface.

- Encouragement should be given to long-range research in high potential areas that have a reasonable chance of success, as well as to projects that would be useful to industry in the short term.

- Industry input should be solicited to assist in developing and prioritizing areas of important research.

- To obtain maximum participation by industry, the activities proposed for industry funding should be project-oriented rather than programmatic, with industry having the freedom to voluntarily participate in the direction of individual projects.

In considering industry's current oil and gas recovery research expenditures (fig. 10), it should be recognized that the vast bulk of project activity is limited to a dozen or so major companies, whose primary R&D effort supports oil and gas operations overseas. Activities in the U.S. focus on high-potential, high-risk frontier areas, such as the Arctic and the deep-water offshore. Most of their research results are, and will remain, proprietary, as is appropriate to the competitive interests of these companies. Although results of some research may eventually be released for publication, much will never be publicly available.

Industry Research Needs and Character of Resource Base

When considering the differences in research needs of the majors and independents, the character of the remaining domestic resource base, especially onshore in the Lower-48, is important. For example:

- Independent operators are pursuing smaller, onshore reserve increments, mostly in the Lower 48. Historically, many independent operators have maintained some access to major company R&D through various farm-out agreements. However, in many areas of the country the majors no longer operate, and this relationship does not exist.

- In contrast to the dozen or so major companies with their own internal research staffs, there are over 20,000 smaller companies and independent operators that have no internal research capabilities. Smaller operators depend on service companies, consultants, and the public sector to support their technology needs.

- Most future Lower 48 onshore reserve additions will come from development of existing fields through extended conventional recovery means (geologically targeted infill drilling), from extensions of existing fields, by discovery of new relatively small fields, and by increased deployment of advanced extraction processes.

- Historically, major multinational oil companies have focused their attention on large-volume fields. With the potential for large-field discovery in the Lower 48 onshore largely realized, most majors have turned their research investment to potentially large-field discoveries in frontier and hostile areas in the U.S. and abroad.

- While economies of scale are realized with large-increment discoveries, the economic benefits from renewed development programs in declining mature fields for both major and independent operators must come from improved efficiencies.

In summary, both major and independent companies control significant oil and gas reserves in the onshore Lower 48, and in this area they have similar technological needs. However, strategies for meeting these needs are very different. Most major oil companies can maintain internal research staffs. Smaller companies and independent operators, in contrast, lack the resources and economy of scale to maintain internal technology staffs and must rely on service companies, consultants, and the public sector for the technical know-how to become more efficient in their operations. As a result, many independent operators can benefit from applied research programs as well as from state-of-the-art public-sector technology transfer programs. The major oil companies, having an internal technology capability, rely more on public-sector research for longer term, fundamental studies.

Research Study Program Description

In April 1988, the Geoscience Institute was awarded a contract from DOE's Office of Fossil Energy to assess the major program elements, research activities, and costs required to establish a comprehensive multidisciplinary geoscience oil and gas recovery research initiative. The general plan and scope for this study were developed based on discussions and reviews with personnel from the Office of Fossil Energy, industry representatives, and the Institute's Board of Directors. From the beginning, there was a strong commitment to develop a broad, multidisciplinary, technical base for support of the study. Therefore, during the course of the investigation, participants with a wide range of technical disciplines from academia, state and federal agencies, and industry were invited to contribute to the effort.

The discussion of the Geoscience Institute's research study process is outlined here first by an explanation of who participated in the study, second by an overview of the study plan or agenda, and then by presentation of the program elements that comprise the research initiative. Next, a synthesis of regional technical program needs is presented based on input from over 400 attendees at six Regional Technical Forums conducted by the Geoscience Institute. Finally, a summary of subcommittee activities focused on identification and prioritization of recommended research activities is described.

Participants in the Study

In total, more than 500 engineers, geologists, geophysicists and other related scientists participated in the study at the regional forum, committee, and subcommittee levels. No other oil and gas recovery research document developed in the public sector has ever incorporated such broad-based technical and regional support. The study was developed through the combined efforts of the following groups.

- The **Board of Directors,** which consists of representatives and alternates from the Institute's member universities and state entities. The Board set Institute policies, approved the final plan for the study, established the Technical Study Committee, and reviewed, modified, and provided the ultimate approval of all study volume reports.
- The **Technical Study Committee** is composed of 16 scientists and engineers regionally representative of Institute member organizations. Responsibilities included definition of the major program elements that provided the basis for identification of research activities, establishment and overview of the Technical Subcommittees, cross-discipline prioritization of the research activities, and preparation of the Summary Program Study Report.
- The six **Technical Subcommittees** were responsible for definition of recommended research areas, identification of research activities, and development of example projects for each of the program elements. These subcommittees were multidisciplinary and composed of equal numbers of industry and academic representatives. They provided the basic technical input and expertise for the program study recommendations and prioritization of research activities within major program elements.
- The more than 400 **Regional Technical Forum attendees** represented state and federal agencies, industry, and academia. Balanced geographic representation of all hydrocarbon-producing regions of the U.S. was achieved by the Institute's hosting meetings at six regional forums in all major hydrocarbon provinces of the United States. Two forums were hosted by the Pacific Region; the primary forum was convened in Los Angeles and a second forum was subsequently held in Anchorage.
- The **Geoscience Institute staff**, headquartered at The University of Texas at Austin, consists of the Institute Executive Director and four Technical Coordinators, two for Engineering, and one each for Geology and Geophysics. The staff was responsible for coordinating program

study activities, handling logistics for all meetings, and, with the guidance of the Technical Study Committee, preparing the Study Summary Report.

Technical Program Study Planning Schedule

The Geoscience Institute's Technical Program Study Planning Schedule consisted of eight major phases, as outlined in table 4. The Department of Energy's Office of Fossil Energy approved the planning proposal and schedule in April 1988, and the Institute held its first organizational meeting in May. The original proposed program study was projected to require 6 months to complete.

Phase 1, Organization

The Institute's Board approved the program planning schedule at its organizational meeting on May 9–10, 1988, in Dallas, Texas. Locations and hosts of the Regional Technical Forums were selected. Program development from the broadest possible range of regional constituents with demonstrated expertise was emphasized.

Phase 2, Interim Report

An interim report, titled "Major Program Elements for an Advanced Geoscience Oil and Gas Recovery Research Initiative," was prepared by the Institute and submitted to DOE in June (1988a). This report defined the major technical program elements of the study and proposed a strategy for their integration. The report also included a survey of the current level of oil and gas recovery research funding in the university and state agency sector.

Phase 3, Regional Technical Forums

In June 1988 the Institute conducted a series of Regional Technical Forums. The goal of the forums was to identify the broad generic, as well as the specific, research needs related to oil and gas recovery in the various hydrocarbon provinces. These forums provided an opportunity for all qualified and interested constituents to participate in the Institute's study program.

Phase 4, Synthesis of Regional Technical Forums

The Institute's Board met jointly with the Technical Study Committee on June 29–30, 1988, in Dallas, Texas, to review program research needs identified by the Regional Technical Forums. In addition, the Technical Subcommittees were established to address the major research program areas identified by the forums. Based on input from the forums, the Technical Study Committee with the Board's approval defined the six major technical elements to be addressed by the Institute's program study:

- Field Reservoir Frameworks
- Reservoir Characterization
- Reservoir Performance Prediction
- Advanced Extraction Technology
- Stimulation and Completion Technology
- Resource Assessment, Data Bases, and Technology Transfer

Phase 5, Program Study Development

The Technical Study Committee met jointly with the Technical Subcommittees on July 19–20, 1988, in Dallas, Texas, to initiate development of the Institute's program study. These subcommittees were composed of recognized experts in their fields. Membership of the subcommittees was multidisciplinary and consisted of personnel from industry, academia, and state agencies (table 5). They were responsible for identification and prioritization of research activities related to specific major program elements. Program recommendations of the Technical Subcommittees and a summary of their program element research activity priorities are presented in Volume II of the Institute's Program Study Report (Geoscience Institute, 1988b).

Phase 6, Subcommittee Presentations to Technical Study Committee

Cochairmen of the subcommittees met jointly with the Technical Study Committee on August 18–19, 1988, in Austin, Texas, to review their research program summary recommendations and research activities priorities. Subcommittee cochairmen and the Technical Study Committee

Table 4. Technical Program Study planning schedule, 1988.

Phase	May	June	July	Aug.	Sept.	Oct.	Nov.	Accomplishment
1. Organization (Dallas, TX)	May 9-10							Set Program Study Schedule and Objectives
2. Interim Report to DOE		June 7						
3. Regional Technical Forums								Defined Regional Research Program Needs
Eastern Region Pittsburgh, PA		June 9-10						
Mid-Continent Region St. Louis, MO		June 9-10						
Rocky Mountain Region Golden, CO		June 13-14						
Pacific Region Los Angeles, CA/Anchorage, AK		June 14-15/June 24						
Gulf Coast Region Houston, TX		June 16-17						
Permian Basin Region Midland, TX		June 23-24						
4. Syntheses of Regional Forums Technical Study Committee (Dallas, TX)		June 29-30						
5. Program Study Development								Identified and Prioritized Research Activities
Charge Technical Subcommittees (Dallas, TX)			July 19-20					
Subcommittee Interim Session			Optional					
Subcommittee Final Sessions			Optional					
6. Subcommittee Presentations of Research Activity Summary				August 18-19				Developed Program Options
7. Technical Study Committee presents program summary to Board (Austin, TX)					September 7-8			
8. Draft of Program Study Summary Report submitted to DOE (Washington, DC)							November 18	Drafted Program Study Report

Table 5. Technical Subcommittee membership.

Field Reservoir Frameworks	
D. J. Benson*	Univ. Alabama
W. R. Jamison*	Amoco Prod. Res.
T. A. Cross	Colorado Sch. Mines
N. F. Hurley	Marathon Oil
J. M. Johnston	Energy Omega
R. Kornbrath	Alaska Oil & Gas
K. L. Larner	Colorado Sch. Mines
R. G. Loucks	ARCO Oil & Gas
R. C. Shumaker	West Virginia Univ.
C. B. Wason	Geophysical Service Inc.
W. L. Watney	Kansas Geol. Survey
Reservoir Characterization	
N. Tyler*	Bur. Econ. Geol., UT
T. Hewett*	Chevron Oil Field Res.
B. Iverson	Univ. Wyoming
H. Jahns	Exxon Prod. Res.
A. G. Journel	Stanford Univ.
S. C. Leininger	Mobil E&P Services
R. L. Mathis	Shell Western E&P
J. A. McDonald	Univ. Houston
D. F. Oltz	Illinois St. Geol. Survey
R. J. Robinson	Texaco Houston Res.
Reservoir Performance Prediction	
L. W. Lake*	Univ. Texas at Austin
H. Kazemi*	Marathon Oil
M. A. Adewumi	Penn State Univ.
A. Carnes	Core Labs
A. Dandona	Mobil E&P
R. E. Ewing	Univ. Wyoming
M. J. King	BP America Inc.
D. A. Lawson	Stanford Univ.
F. M. Orr, Jr.	Stanford Univ.
Advanced Extraction Technology	
D. W. Green*	Univ. Kansas
R. N. Healy*	Exxon Prod. Res.
J. L. Cayias	Sun E&P Co.
L. L. Handy	Univ. So. California
J. S. Hanor	Louisiana State Univ.
M. M. Prats	Shell Development
F. I. Stalkup	ARCO Exploration Tech.
W. C. Tosch	Penn State Univ.
E. J. Witterholt	Standard Oil Prod.
Stimulation and Completion	
R. A. Startzman*	Texas A&M Univ.
R. W. Veatch*	Amoco Prod. Res.
J. Brill	Univ. Tulsa
G. R. Coulter	Sun E&P Co.
A. Daneshy	Halliburton Services
J. T. Engelder	Penn State Univ.
A. D. Hill	Univ. Texas at Austin
Resource Assessment, Data Bases, and Technology Transfer	
J. M. Forgotson*	Univ. Oklahoma
W. F. Diggons*	Schlumberger
S. Ameri	West Virginia Univ.
K. Aminian	West Virginia Univ.
S. Bhagwat	Illinois St. Geol. Survey
J. S. Fischer	Landmark Graphics
J. D. Grace	ARCO E&P
C. G. Groat	Louisiana Geol. Survey
R. A. Mason	Mason Production
E. H. Mayer	THUMS Long Beach Co.
E. D. McKay	Illinois St. Geol. Survey
D. E. Powley	Amoco Prod. Res.
P. R. Rose	Kansas State Univ.
P. H. Stark	Petroleum Information

*cochairmen

jointly developed a cross-element prioritization of research activities to establish a ranking of first-priority activities for a limited funded program.

Phase 7, Technical Study Committee Presentation to the Board

The Technical Study Committee and subcommittee cochairmen met jointly with the Board of Directors on September 7–8, 1988, in Austin, Texas, to review their recommended program priorities. The Board accepted the committee's program recommendations with minor modifications.

Phase 8, Finalization of Program Study Summary Report

The Institute's four Technical Coordinators, working with the Technical Study Committee, developed a preliminary draft of the "Recommendations and Program Study Summary Report, Research Activity Priorities" (a draft of this publication), for submittal to DOE in November 1988.

Major Technical Program Elements

The six major technical program elements that formed the basis for the program study were defined by the Technical Study Committee and approved by the Board and are briefly described below.

(1) Field Reservoir Frameworks
The occurrence and distribution of reservoirs and their intrafield variability are controlled by the stratigraphic and structural frameworks. Targeting development wells to extend field limits, test undrained fault segments, and evaluate deeper pool potential requires interpretation of the geological framework for the field. Field framework studies also provide a basis for detailed reservoir characterization.

(2) Reservoir Characterization
Improved reservoir models delineating patterns of geologic heterogeneities are required to determine the distribution of reservoir flow units (that is, intervals of bypassed high oil saturation) and to target remaining mobile oil, immobile oil, and untapped natural gas resources in existing fields. Reservoir characterization studies provide the basic input required for development of simulation models to predict and analyze production performance.

(3) Reservoir Performance Prediction
In order to provide more accurate simulations of production, improved methods for quantification of interwell geologic heterogeneity patterns must be developed. More accurate interwell reservoir descriptions will provide better definition of flow units for estimating production performance as well as enhancement of advanced recovery applications.

(4) Advanced Extraction Technology
Enhanced oil recovery (EOR) processes can increase recovery of both mobile and immobile oil. Improved understanding of capillarity, mobility, and miscibility and their relationship to reservoir recovery processes is required to make EOR processes more cost effective and more broadly applicable.

(5) Stimulation and Completion Technology
Unswept oil and gas in low-permeability zones are significant targets for additional recovery. Accurately contacting these bypassed pay zones requires improved formation evaluation, well completion techniques, and stimulation methods.

(6) Resource Assessment, Data Bases, and Technology Transfer
The characteristics and geologic and geographic distribution of hydrocarbon resources for existing fields need to be documented. Such a data base will provide a basis for regionally prioritizing and selecting areas for technology deployment and research emphasis. The success of the advanced geoscience research initiative will depend on how well new understandings, concepts, and technological developments can be transferred to the operators and service companies. Efficient technology transfer requires establishing effective publications, special seminars and workshops, continuing education courses, and joint cooperative programs with industry.

Inventory of Regional Needs

The focus of the Institute's Regional Technical Forums was on identifying oil and gas recovery problems in selected hydrocarbon provinces, as well as broader generic problems. Reports of the Regional Technical Forums (Geoscience Institute, 1988c) provided a resource for the Technical Subcommittees in their development of recommendations for research programs.

Forum meetings were held in Pittsburgh, Pennsylvania, for the Eastern Region; St. Louis, Missouri, for the Mid-Continent; Houston, Texas, for the Gulf Coast; Odessa, Texas, for the Permian Basin; Golden, Colorado, for the Rocky Mountain Region; and Los Angeles, California, and Anchorage, Alaska, for the Pacific Region (table 6). More than 400 scientists and engineers from academia, state and federal government, and industry participated in the forums. Two hundred sixty-eight (65 percent) of the participants were from academia and govern-

Table 6. Geoscience Institute Regional Technical Forums.

Region	Location	Date (1988)	Forum attendees: Academic/ Government	Industry	Total
Eastern	Pittsburgh, PA	June 9 - 10	24	13	37
Mid-Continent	St. Louis, MO	June 9 - 10	56	11	67
Rocky Mountain	Golden, CO	June 13 - 14	47	21	68
Pacific	Los Angeles, CA	June 14 - 15	43	12	55
	Anchorage, AK	June 24	8	11	19
Gulf Coast	Houston, TX	June 16 - 17	61	49	110
Permian Basin	Odessa, TX	June 23 - 24	29	25	54
		TOTAL	**268**	**142**	**410**

35% Industry Participation

ment entities, and 142 (35 percent) were from industry.

Information provided by the Regional Technical Forum reports was used to develop a national perspective on oil and gas recovery research program needs. Regional program recommendations and a synthesis of research needs based on input from the Technical Forums (Geoscience Institute, 1988c) are briefly described in the next sections.

Eastern Region

The Eastern Region is the oldest and most mature hydrocarbon-producing province in the United States. All oil production from the region is from Paleozoic sandstone and carbonate reservoirs and is dominated by stripper wells characterized by high water cuts. For example, in 1986 in Pennsylvania, an average of 10,000 BOPD was produced from 14,200 wells. Eastern Region reservoirs are relatively shallow, enabling development at moderate costs, thus providing significant incentives for independent operators.

The lack of standardized, systematic production records and reservoir data bases is a fundamental problem in the Eastern Region. Compilation and synthesis of the geographic and geologic distribution of remaining unrecovered mobile and immobile oil resources are needed for developing a comprehensive recovery research program plan for the region.

Research activity recommendations by Eastern Region Forum participants emphasized the need for development of low-cost well treatments and performance prediction techniques to maximize recovery from high-water-cut stripper wells. Environmentally acceptable, low-cost water disposal techniques are also a major need. An effective continuing education program to transfer existing technology to the independent operators is an additional high-priority research activity identified by the Eastern Region.

Mid-Continent Region

As in the Eastern Region, oil production in the Mid-Continent is dominated by the region's 190,000 stripper wells. In 1987, more than 75 percent of the 275 MMBO produced in the Mid-Continent was contributed by stripper well production. The area is characterized by Paleozoic reservoirs with a higher than average percentage of complex carbonate reservoirs. Total unrecovered remaining mobile oil resources are estimated to be over 13 Bbbl.

Currently, in-place extended secondary recovery programs in much of the region suggest that the highest priority research opportunities for increased recovery efficiency include EOR programs, improved methodology for geologically targeted infill drilling, extension of known reservoirs through predictive interpretations of trap and porosity development, and evaluation techniques for deeper pool potential below existing field pays. More specifically, a systematic characterization of the region's reservoirs by play and trap type is required for defining specific future research program needs. Such a study would allow identification of the major controls on reservoir heterogeneities in the region.

The Mid-Continent Forum participants emphasized technology needs of the independent smaller operator, especially methods for improving single well productivity and recovery, in addition to larger scale field recovery programs. For example, development of inexpensive PC computer reservoir/well simulation routines and software packages to handle development risk analysis would be particularly useful. The highest priority need identified by the Mid-Continent's Advanced Technology Extraction Panel was development of improved flow-diverting agents for modification of in situ permeability.

Gulf Coast Region

Onshore Gulf Coast oil and gas production is from a wide range of Mesozoic and Tertiary sandstone and carbonate reservoirs characterized by a variety of complex to simple structural trap types. Less than 25 percent of the region's annual production of more than 400 MMBO is derived from stripper wells. Remaining unrecovered mobile oil resources in the region's existing fields are estimated to exceed 20 Bbbl.

Gulf Coast Forum participants stressed the need for establishing dedicated subsurface test facilities for a variety of reservoir types to enable testing new methods, models, concepts, and tools at a true scale. They also emphasized the need for development of improved surface seismic systems and borehole imaging tools.

The Gulf Coast Forum's Reservoir Characterization Panel concluded that improved methods for characterizing interwell horizontal and vertical heterogeneity were one of the highest research priority needs. Consensus of their Advanced Extraction Technology Panel was improved miscible and chemical flooding processes have the greatest potential impact for enhanced recovery from Gulf Coast area reservoirs containing light oils.

Permian Basin Region

The Permian Basin is a world-class petroleum province that has reached exploration maturity. A cumulative volume of 25.3 Bbbl of oil has been produced from reservoirs that contained at discovery a total of 105.7 Bbbl of oil. It is estimated that use of current technology will recover less than 30 percent of the original oil in place from existing reservoirs. Production is predominantly from carbonate reservoirs, and over 50 percent is from reservoirs developed in restricted marine-platform depositional systems. Other types of depositional systems that contain significant oil resources are platform-margin carbonates, open-shelf carbonates, carbonate buildups, and submarine-fan sandstones.

The highest priority need in the Permian Basin Region is the development of methods to define reservoir boundaries and characterize the internal petrophysical architecture within a stratigraphic facies framework. Reservoir boundaries and the internal heterogeneities of carbonate reservoirs are stratigraphically controlled. Quantification of stratigraphic variables for input to computer simulation models is critical for improving recovery from existing reservoirs.

Miscible-gas flooding, using carbon dioxide, and waterflooding are the current dominant enhanced recovery processes being used in the Permian Basin. The principal research needs for improving recovery using these processes include better reservoir management systems, improved methods for integration of geologic heterogeneity into process prediction techniques, and methods for proper scaling of rock properties and laboratory results.

Rocky Mountain Region

Oil and gas production in the Rocky Mountain Region is from a wide variety of sandstone and carbonate reservoirs predominantly of Permian-Pennsylvanian and Cretaceous age but also including Tertiary lake beds of the Green River Formation. The region is structurally complex and characterized by large-scale block-faulting, overthrusting, and folding. This results in complex tectonic controls in addition to depositional and diagenetic process controls that have a significant influence on the performance of reservoirs. Uplift associated with tectonism has provided outcrops of productive formations in proximity to producing reservoirs. Such outcrops provide an excellent opportunity to observe firsthand the continuity of productive horizons and scale of reservoir heterogeneities.

The highest priority need identified by the Rocky Mountain Forum participants was a better understanding of the spatial variability of storage and flow units for specific reservoir types.

Because of the tectonic control exerted on many Rocky Mountain reservoirs, natural fracturing and its effects on reservoir performance should be investigated. Therefore, Rocky Mountain Forum participants placed a high priority on developing three-dimensional characterizations of petrophysical parameters for fractured reservoir simulation and evaluation of the application of EOR processes.

Another goal is to develop a knowledge base/expert system for integrating multidisciplinary information gained from reservoir studies. A comprehensive data base is fundamental to the operation of such a system because it would archive the research results, and it would facilitate comparison between Rocky Mountain reservoirs.

Pacific Region

The Pacific Region includes the mature producing province of California and the relatively new producing province of Alaska. Both areas produce primarily from sandstone reservoirs, and California has significant production from the fractured Monterey chert. Most of the commercial heavy oil reservoirs in the U.S. today are in the Pacific Region. California has developed an estimated total OOIP of 38 Bbbl of heavy oil, whereas Alaska is estimated to have 24 to 40 Bbbl of heavy oil in place pending development. Total original volume of oil in California is estimated at 85 Bbbl, of which 27 Bbbl will be produced using current technology, resulting in 69 percent of the OOIP being left in the reservoirs.

A major need in the Pacific Region is for more realistic, quantitative characterization of geologic reservoir heterogeneities, especially in fractured, low-permeability, high-porosity reservoirs such as the Monterey chert. New methods are needed for inputting this information into reservoir simulation models for performance prediction in order to provide quantitative predictions of various recovery strategies for fractured reservoirs.

The Pacific Region Forum concluded that there was significant need to better understand the impact of geologic heterogeneities on the thermal recovery process and to develop methods of applying thermal recovery processes to light oil reservoirs such as the fractured Monterey reservoirs. In Alaska, methods of applying thermal recovery processes to shallow heavy oil reservoirs in areas of permafrost need to be developed.

General Forum Research Needs

In addition to specific regional research needs, forum participants recognized a number of similar, more general, broader based national program opportunities. The most important of these are

- Characterization of interwell reservoir heterogeneities
- Development of integrated, multidisciplinary projects focused on specific field studies
- Creation of a standardized national reservoir/resource assessment data base
- Quantification and scaling of variables for computer reservoir simulation and performance prediction
- Improvement of mobility control agents to increase reservoir sweep efficiency
- Provision for timely and effective technology transfer to oil and gas operators, both majors and independents.

Identification of Research Activities

The Technical Subcommittees drew heavily from the Regional Technical Forum reports and from their own personal experience in developing their major program element research reports. The Technical Study Committee provided appropriate guidance.

The Institute's Technical Coordinators developed a format to guide preparation of subcommittee reports. First, each major technical program element was subdivided into individual key research areas. Second, research activities were identified by area. Finally, on a selected basis, identified projects were related to research activities. The research activities represent the basic building blocks of the research study plan and essentially correspond to a program-level status. As outlined in figure 10 (p. 22), the subcommittees subdivided the technical program elements into 41 research areas and 166 associated research activities and identified 289 example projects. A numerical listing of research areas, activities, and example projects by major program elements is presented in figure 11.

The subcommittees worked independently, with the Institute's Technical Coordinators providing liaison. As expected, in some cases the

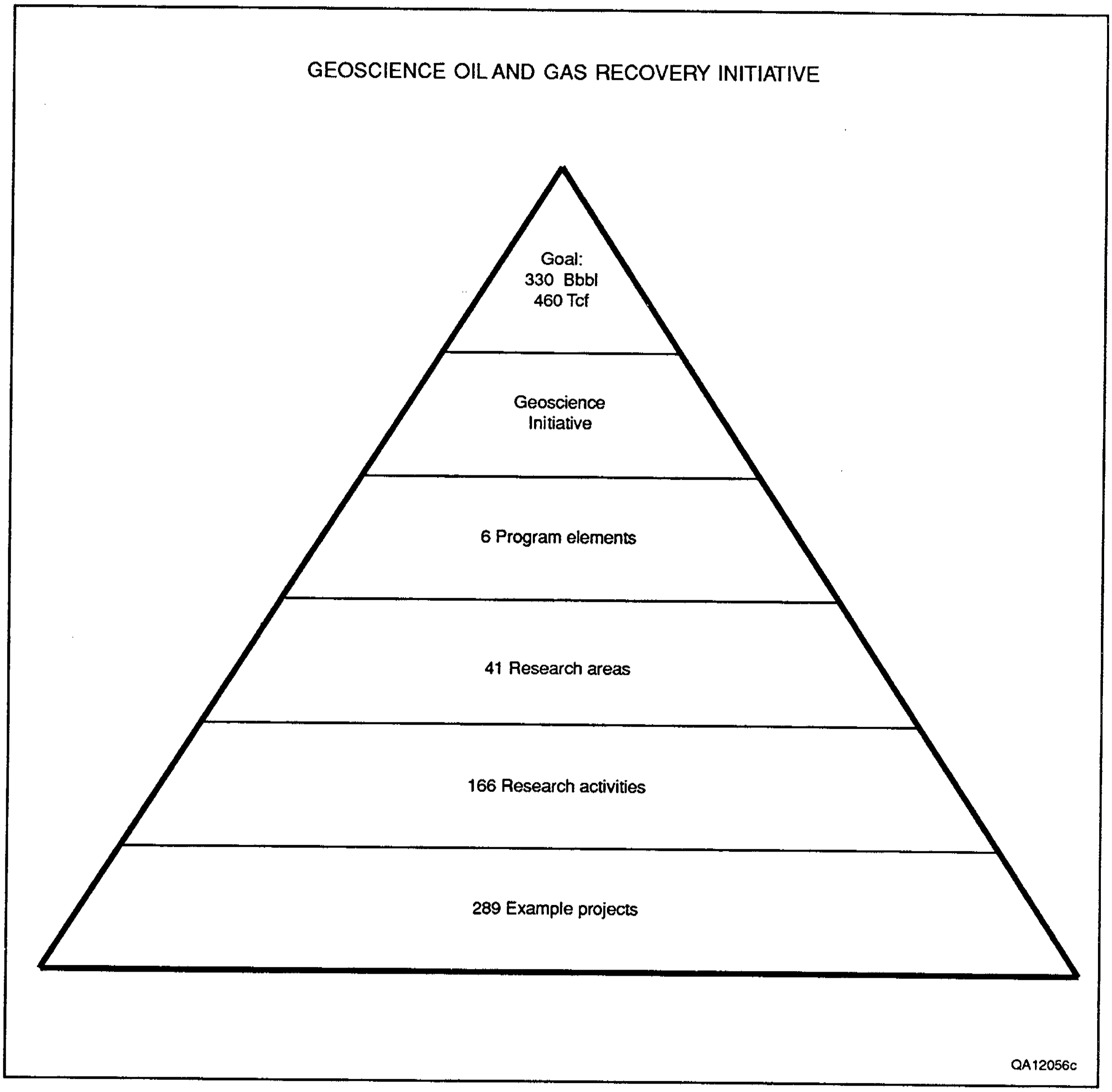

FIGURE 11. Development of Technical Committee Program Study.

subcommittees identified similar research activities and projects. There was no attempt to remove duplication or redundancy in the final subcommittee reports. The Technical Study Committee and the Institute's Technical Coordinators were responsible for synthesizing the subcommittee reports and developing an integrated recommendation for a study program. In preparing their program reports, the subcommittees priority-ranked research activities into first-, second-, and third-order priority categories in order to identify the most critical research needs.

Rationale for Program Options

Successful implementation of the new geoscience oil and gas recovery initiative depends on effective integration of several key issues related to development of the research programs. These key issues include (1) establishment of reasonable program funding levels, (2) development of an effective multidisciplinary team approach, (3) identification of research activity priorities, and (4) implementation of an effective technology transfer program.

Funding of Public-Sector Recovery Research

The vast majority of the public sector's non-federal oil and gas recovery research is conducted at more than 20 research universities and state agencies distributed across the United States. For the most part, research project activities are carried out independently within individual university departments and state agencies. Increased funding support of these programs would provide opportunities for enhancement of multidisciplinary programs and joint efforts between universities and between universities and industry that would provide a better integration of current research activities.

Based on a survey of research universities and state agencies engaged in advanced oil and gas recovery research, it was determined that current funding for the program effort is about $38 million (fig. 12). For the purposes of the survey, non-overheaded state support, university funding, and industrial associate contributions were normalized by increasing them on average by 50 percent to facilitate comparison to federally funded programs.

The greatest support for the current research effort comes from state appropriations (35 percent) and industry contracts and grants (31 percent). The federal government, primarily through DOE, supports an estimated 16 percent of the current oil and gas recovery research effort. Most of the federal funding by DOE supports advanced extraction process technologies. Industry support since 1985 has been significantly reduced and is currently provided primarily through industrial associate groups established at various universities. GRI (5 percent) has recently increased support for assessment and improved recovery efficiencies

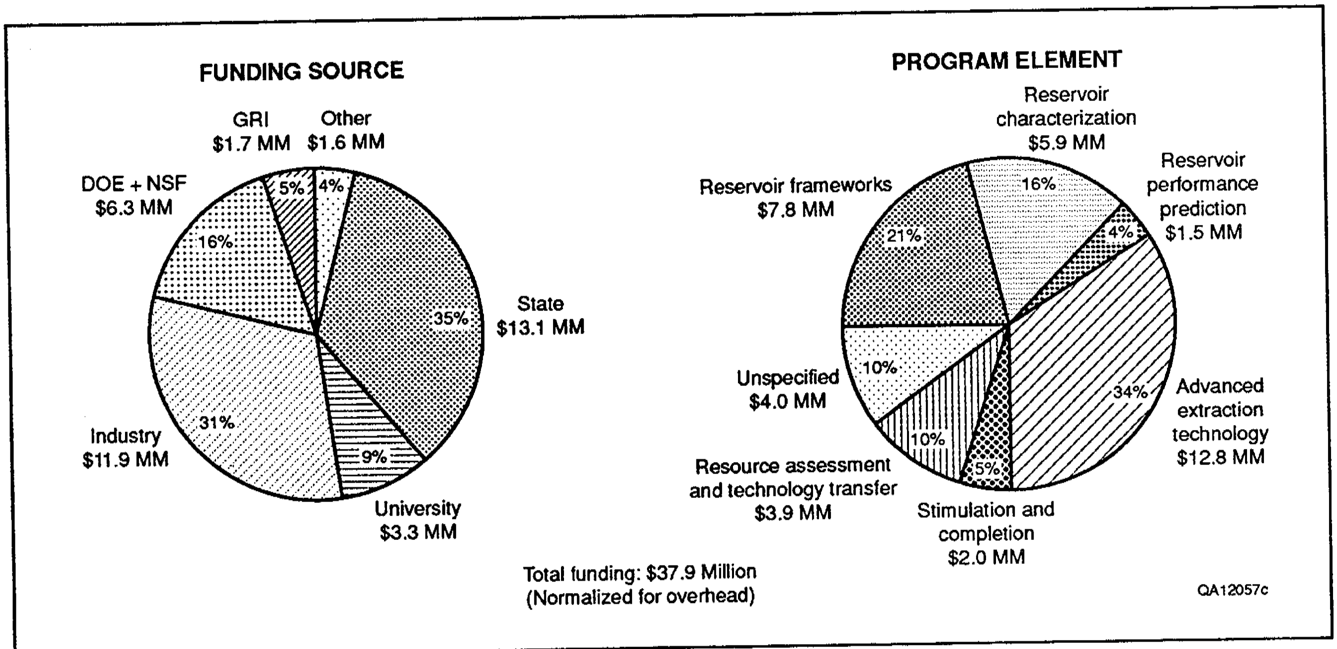

FIGURE 12. Current university and state FY88 program recovery research funding levels, based on a national survey of 21 universities and state surveys.

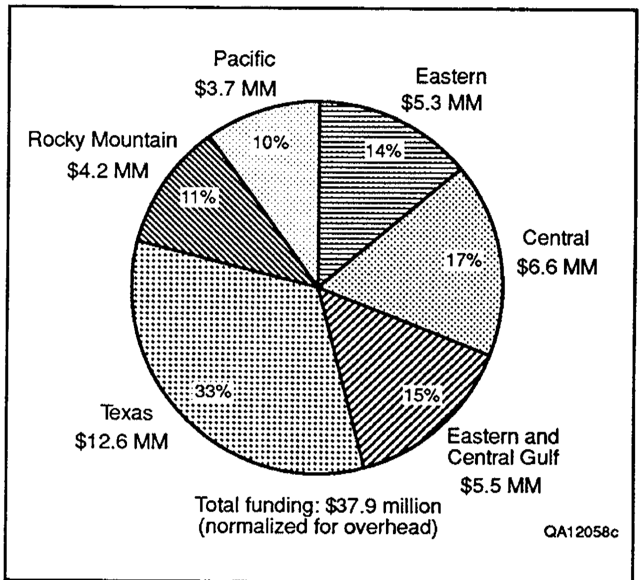

FIGURE 13. Current FY88 program funding levels, by U.S. region.

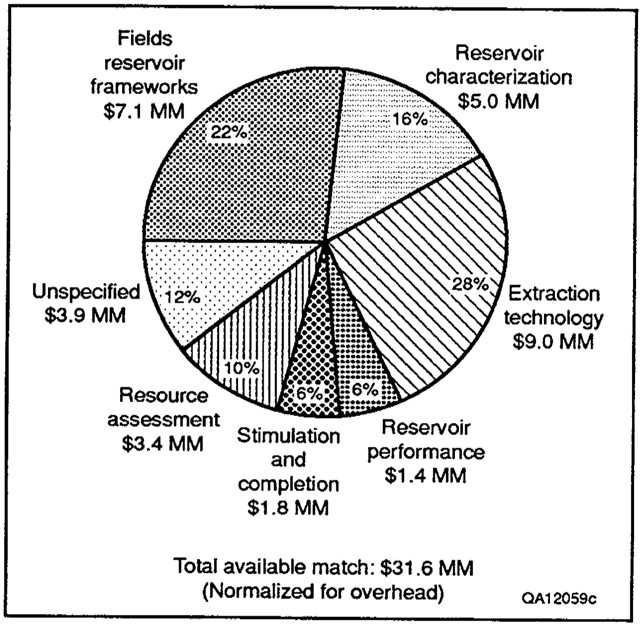

FIGURE 14. Current non-federal FY88 program funding available for cost-sharing.

related to gas reservoirs. State funding, for the most part, is dedicated to reservoir characterization and resource assessment studies focused on state lands, as well as providing support for oil and gas data base development and core and sample curation. Support from technical societies, private foundations, and trade associations accounts for an estimated 4 percent of the total effort and is grouped in the "Other" category.

The major emphasis of current oil and gas recovery research programs is on development of Advanced Extraction Technologies (34 percent) and Reservoir Frameworks (21 percent). Support for Reservoir Characterization, Reservoir Performance Prediction, Stimulation and Completion Technology, and Resource Assessment, Data Bases, and Technology Transfer ranges from 4 to 16 percent for each area. A variety of related recovery program activities, such as oil characterization, drilling technology, and seismic acquisition systems, is included in the "Unspecified" category. However, information supplied in the survey was too general to categorize these activities by specific program element.

Regional summaries of survey results outlined in figure 13 indicate that the greatest funding support for recovery research is centered in Texas (33 percent). The Central (17 percent), Eastern and Central Gulf (15 percent), and Eastern regions (14 percent) all have similar levels of activity. The Rocky Mountain (11 percent) and Pacific regions (10 percent) have slightly lower levels of activity. However, it is generally felt that survey results are incomplete and that in all regions, particularly the Pacific Region, funding levels are understated.

Available Program Matching Funds

In the Senate-House Conference Report (August 1988) on support of consortia for geoscience oil and gas recovery research, it was proposed that funding be cost shared. Of the identified $38 million, federal funds account for only $6.3 million, thus providing more than $30 million for cost sharing with the new DOE oil and gas recovery research initiative.

Matching funds available on a program element basis are outlined in figure 14. The Advanced Extraction Technology and Field Reservoir Frameworks areas have the largest available matching fund reserves at $9 million and $7.1 million, respectively. Matching funds available for the Reservoir Characterization and Resource Assessment, Data Bases, and Technology Transfer areas total $5.0 million and $3.4 million, respectively. The Reservoir Performance Prediction and Stimulation and Completion Technology areas have smaller amounts available for matching consideration. Including a requirement for a strong matching fund component for participation in DOE's new geoscience research initiative optimizes the program effort. It ensures that organizations with established advanced recovery research programs will be the major participants. A matching requirement also encourages industry and states to join the program in order to participate and benefit in a highly leveraged, cost-shared research effort. The reduction in industry's recovery research effort since 1985 can be partially offset by a joint industry and university/state agency cooperative program supported by DOE-matched funding.

Multidisciplinary Team Approach

A multidisciplinary team approach is required to maximize research results from improved recovery research programs. Major technical program elements and links between elements that comprise the research program are outlined in figure 15. The degree of involvement of geologists, geophysicists, and engineers in any particular program element is suggested in figure 16. Results from geological, geophysical, and engineering research studies provide slightly different perspectives on hydrocarbon recovery research problems. Information developed by each discipline builds on information from the others, and only through their effective integration can research results provide the level of understanding required to design efficient improved recovery programs.

Such a program can be successful only if specific, relevant, integrated interdisciplinary research proposals are developed. Further, opportunities must be identified to encourage full industry partnership in the research program, not only to promote adequate matching funds but also to expedite constructive surveillance of technological progress and to facilitate technology transfer. For the most part, these objectives can best be achieved where well-established, widely recognized oil recovery projects are present in the same institution.

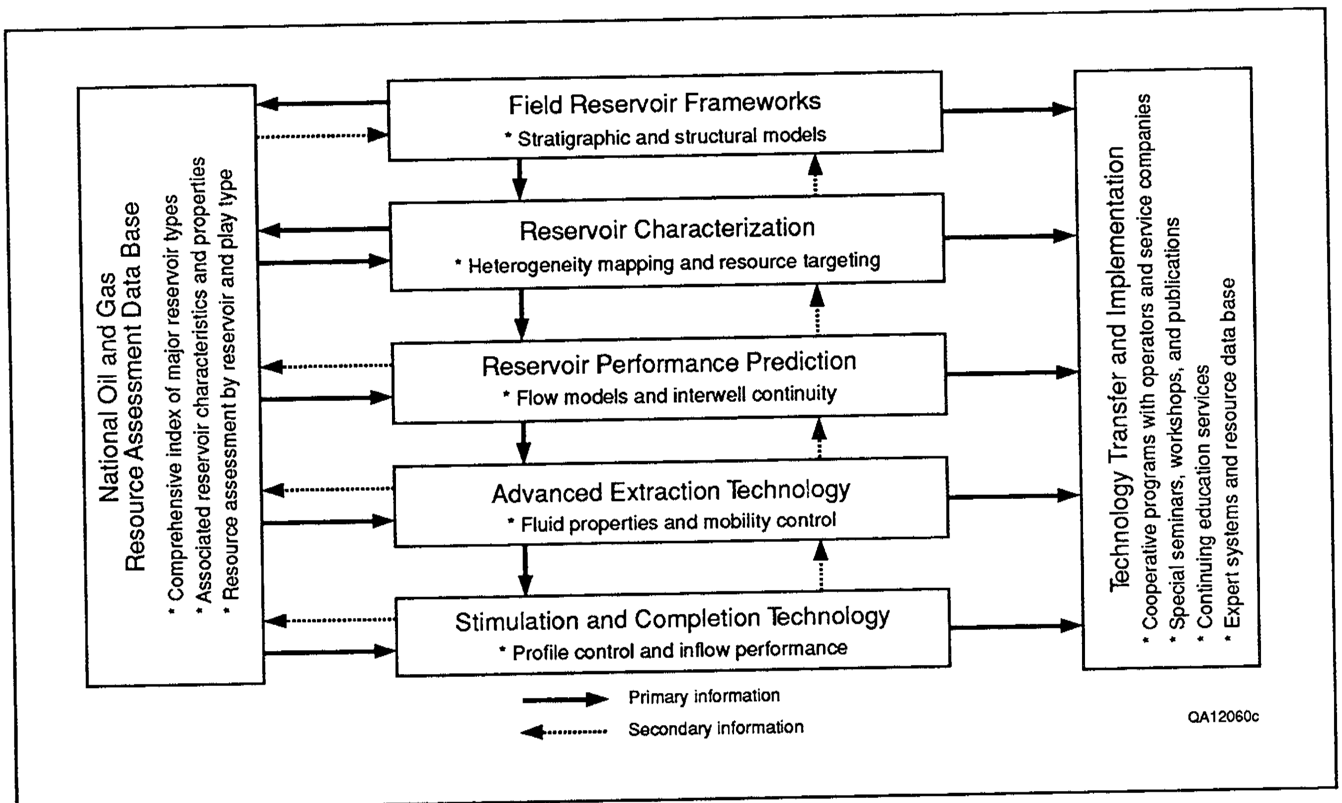

FIGURE 15. Strategy for integrated multidisciplinary approach.

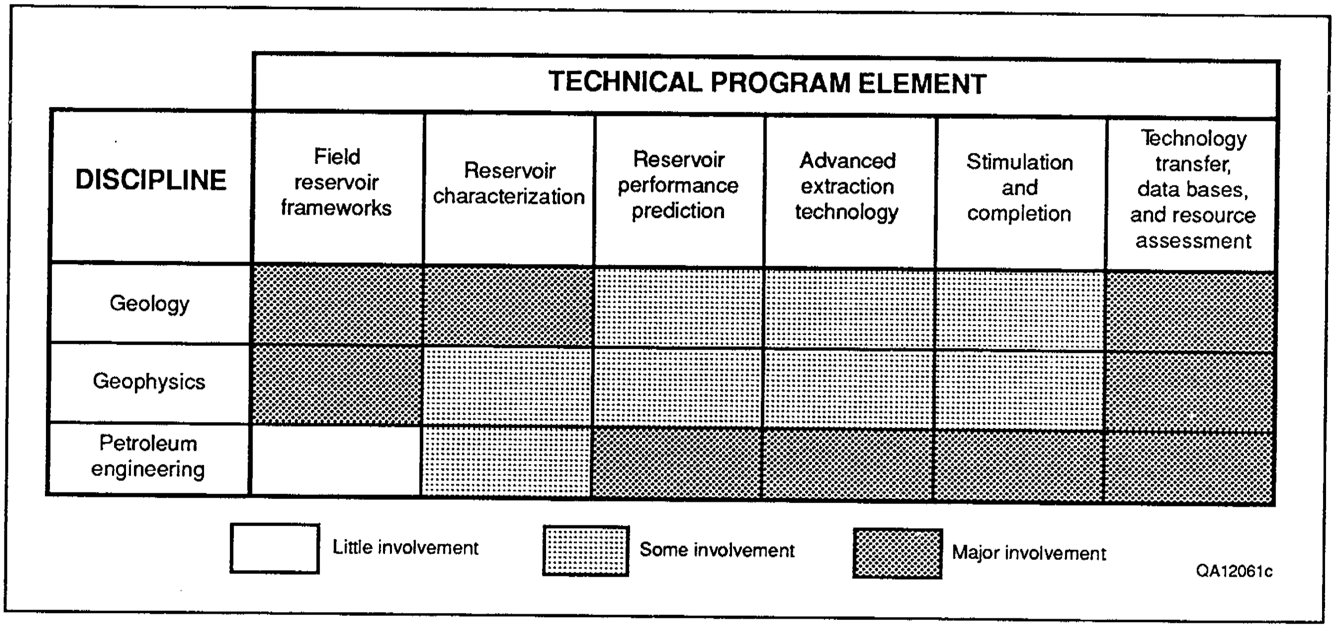

FIGURE 16. Technical Program Element involvement, by discipline.

A basic requirement for a balanced interdisciplinary research program is identification of common research interests and goals among adequately staffed and equipped entities. Established expertise and guidance in program planning, execution, and evaluation are essential. The greatest progress will be made if jointly coordinated programs are fostered.

A program of this nature can best be achieved by focusing on specific reservoir types. The distribution of reservoirs in a field and variability of their properties are largely controlled by reservoir genesis, which is a function of depositional, diagenetic, and tectonic processes. Field reservoir framework studies are useful in defining genetic differences between reservoirs and provide a basis for model development for classifying reservoirs, predicting reservoir geometries, and describing the characteristics of reservoir heterogeneities.

Models must be constrained by specific reservoir interpretations developed through integration of core, wireline log, and geophysical data. This will provide three-dimensional information with which to map reservoir heterogeneity and to locate major resource targets. In addition, the reservoir must be characterized in engineering terms in order to be used quantitatively. Likewise, reservoir descriptions derived from geologic and geophysical interpretation must be used to interpret engineering data such as tracer surveys and pressure analyses. Production history, when combined with geologic interpretations, can provide additional insight into the controls of reservoir heterogeneity on performance.

Geological and geophysical information must be utilized in extraction research, and the results of extraction research can provide important information on what geologic features have significant effects on process performance. Starting on the microscale, pore-space morphology and rock mineralogy, along with other physical and chemical properties, control basic transport and displacement mechanisms. On a larger scale, the efficient exploitation of the reservoir is ultimately controlled by the degree of continuity between wellbores. Scaling-up of EOR laboratory results to field scale requires knowledge of the effects of reservoir heterogeneities and flow pattern variability on process performance.

Stimulation and completion research needs to take geological considerations into account. Research into chemical treatments involves knowledge of in situ mineral and fluid properties and the distribution of those properties in the reservoir. Investigation into the design of fracture treatments requires knowledge of the state of stress in the formation and the distribution of rock-strength properties, properties that can be related to geophysical measurements and to geologic processes.

Ultimately, improved commercial recovery from existing reservoirs will depend upon having available accurate methods of predicting reservoir performance. One of the key problems in reservoir performance prediction is portraying geologic information by sets of numbers that result in accurate representation of the fluid transport properties of a reservoir. Geologists, geophysicists, and engineers will have to work together in order to develop methods of integrating engineering numerical data and semiquantitative geologic data for the purpose of computer simulation of reservoir performance.

Multidisciplinary Recovery Research Programs

Based on review of research activities identified by the Technical Subcommittees, the three following categories for development of multidisciplinary research programs are recognized.

(1) Reservoir Heterogeneity
This category includes research activities aimed at improved understanding and mapping of matrix heterogeneities to delineate distribution of mobile and immobile oil. In addition, methods for defining and developing techniques to reduce the effect of matrix heterogeneities on extraction processes, as well as methods for refining quantitative and descriptive information for reservoir simulation, are included in this category.

(2) Reservoir Geomechanics
The reservoir geomechanics program includes research activities that focus on methods of characterizing fractured reservoirs, better understanding of the structural controls on hydrocarbon distribution and fluid flow, improved induced-fracture well treatments, and improved methods to predict performance of fractured reservoirs.

(3) Rock/fluid Interactions
This program includes research activities focused on interaction of natural, as well as introduced, minerals and fluids in the reservoir. Improved understanding of mineral equilibria and kinetics of reactions at in situ reservoir conditions is required for development of modeling techniques for prediction of reservoir quality and production performance.

Prioritization of Research Activities

As previously mentioned, the Technical Subcommittees identified a total of 166 research activities, requiring an estimated research program funding level of approximately $125 million. To develop optional program opportunities at reduced funding levels, the Technical Subcommittees prioritized research activities into first-, second-, and third-priority needs. Priority ranking of research activities by the Subcommittees was based on the following criteria:

- Potential Payout
  First-priority research activities must have a relatively high potential benefit or payout. If successful, they can greatly advance the science and technology associated with their application.

- Multidisciplinary Approach
  Activities that require cross-discipline support and provide interfaces between disciplines were generally ranked higher than more narrowly focused research activities.

- Probability of Success
  Research activities identified with new approaches that were judged most likely to provide successful results were generally ranked higher. Certain high potential payout activities with low chances of success were generally ranked lower.

- Public Sector Capability
  Activities were ranked on their appropriateness to be undertaken by joint industry/public sector research entities. Certain research activities are best suited to be carried out singularly within industry; therefore, the more high-cost activities requiring large research staffs and unique analytical or field test facilities were generally ranked lower.

- Match Funding Opportunities
  It was recognized that the major operating companies would be more inclined to support research activities that complemented their ongoing, established programs. Therefore, the subcommittees attempted to identify higher priority research activities that did not directly duplicate industry's research efforts.

Based on these prioritization criteria, the subcommittees independently identified 64 top or Priority-1 research activities. Likewise, 60 Priority-2 and 40 Priority-3 research activities were identified.

In light of anticipated limits on potential early program funding for oil and gas recovery research, the activities were further prioritized to better focus on the highest priority needs. The subcommittee cochairmen together with the Technical Study Committee ranked all 64 Priority-1 research activities by program element into top (A), middle (B), and lower (C) categories. On this basis, 24 Priority-1, A-ranked activities were identified. Likewise, 18 Priority-1, B-ranked, and 22 Priority-1, C-ranked activities were identified. Finally, a cross-program-element prioritization and forced ranking of all Priority-1, A-ranked research activities were made, thus providing a sequential priority listing of the top 24 research activities.

Technology Transfer

Technology transfer is perhaps the most important aspect of any research effort because it provides the opportunity to prove the applicability of research results. Within the scope of the geoscience initiative, however, it is not a research activity but a requirement for successful completion of any research effort. The methods of communicating research results should be tailored to the technical level of the operators and to regional needs.

As discussed in the Domestic Oil and Gas Industry section (p. 21-24), the technical level among operators is highly variable. Major oil companies with highly developed internal research capabilities maintain a high level of technical expertise, whereas the technical capabilities of smaller, independent oil operators are usually more limited. To communicate research results to smaller, independent oil operators it may be necessary to first introduce a broad-based level of existing technology before discussing research results. Technology transfer to major companies would be more focused on basic, fundamental research results. Funding for the technology transfer activity is important, but it should be considered separately and apart from funding for research activities.

Recommended Program Priorities

The primary goal of the Geoscience Institute's oil and gas recovery research study is the identification of short- to mid-term program opportunities and priorities for improved oil and gas recovery efficiency in order to increase reserves and production from existing reservoirs. The study is confined to recovery research areas, not exploration, and is specifically focused on development of improved understanding of controls on reservoir heterogeneities and techniques that provide for improved mapping, simulation, and extraction of unrecovered mobile oil, immobile oil, and untapped gas in already discovered fields. This study does not address research activities related to equipment and instrument development, drilling and casing innovations, or environmental issues. These areas, for the most part, are peripheral to the central oil and gas recovery research program study as set forth in the Institute's contract.

The Institute and its committees, coordinating input from all segments of the petroleum community, have developed comprehensive research recommendations with priorities and options as outlined in the following section. The program scope of this new initiative can be significantly widened with the addition of matching funds from nonfederal sources and provides opportunities for both industry and DOE to participate in high-leveraged, cost-shared research efforts.

Program Option Development

Based on evaluation and ranking of the 64 Priority-1 research activities, the Technical Study Committee developed a series of integrated multidisciplinary and individual-discipline program options at $10 million, $20 million, and $50 million levels. To eliminate overlap and redundancy of Priority-1 research activities, certain activities were combined.

The 10 highest ranked research activities identified by the Technical Study Committee compose the $10 million program option. Nine of the activities are focused on multidisciplinary reservoir heterogeneity studies (fig. 17). The tenth activity pertains to assessment of mobile and immobile oil resources related to development of a national data base. Other related reservoir heterogeneity activities are added in the $20 million and $50 million programs. A technology transfer activity is shown as an eleventh element of the $10 million program, but it is recommended that this effort be separately funded.

The $20 million program builds on the $10 million program with the addition of a group of related activities focused on reservoir geomechanics studies, reflecting the need for improved understanding and mapping of fractured reservoirs and fracture techniques. Four additional reservoir heterogeneity activities and five individual activities are also included in the $20 million effort.

The $50 million program includes a third integrated multidisciplinary program effort related to rock/fluid interactions and includes additional reservoir heterogeneity and reservoir geomechanics research activities. Most of the individual-discipline activities are included in the $50 million program, reflecting the consensus of the Technical Study Committee that

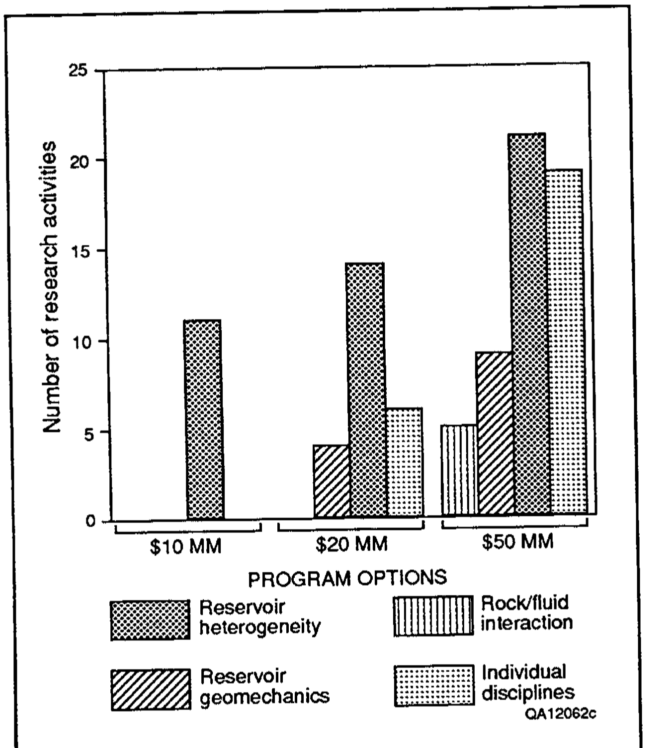

FIGURE 17. Recommended program option priorities.

integrated, multidisciplinary efforts have priority over individual activities. In addition, the committee recommended that worthwhile Priority-2 and Priority-3 research activities should be given consideration for funding if high-quality research proposals are submitted.

$10 Million Multidisciplinary Program Option

The $10 million program includes the 10 highest priority research activities force-ranked across program elements (table 7). The Technical Study Committee recognized that one of the most critical program requirements is development of an improved national oil and gas assessment data base system. Such a system is required to help identify regional priorities for key fields and reservoir types to be studied.

The primary research thrust of the $10 million program is an integrated, multidisciplinary reservoir heterogeneity effort. The program includes activities related to improved understanding and mapping of reservoir heterogeneity, defining and reducing the effect of heterogeneity on extraction processes, and finally developing improved methods for quantifying geological descriptions for input into the reservoir simulators for performance prediction.

To develop improved heterogeneity mapping methods, the geologic controls on heterogeneity must be delineated at various scales. Stratigraphic sequence models address the intrafield or megareservoir heterogeneity scale, whereas outcrop and subsurface well log and core studies address the interwell scale. Results from these studies must be integrated with high-resolution, 3-D seismic and multicomponent seismic investigations that provide important constraints for subsurface reservoir characterization models. In addition, geostatistical methods provide an improved methodology for extrapolation of interwell heterogeneities and development of 3-D reservoir models. Investigations related to advanced extraction technology include devel-

Table 7. Prioritized $10 Million and $20 Million Program Options.

$10 Million Level	$20 Million Level (Additional Activities)
Reservoir Heterogeneity	**Reservoir Geomechanics**
• Simulation Averaging Procedures	• Rock Mechanics and In Situ Stress Characteristics
• Controls of Geologic Heterogeneity on Reservoir Performance	• Simulation and Modeling Hydraulic Fracturing
• Reservoir-Scale Outcrop Investigations	• Structural Style Models for Reservoir Frameworks
• 3-D High-Resolution Seismic Mapping	• Geophysical Methods for Characterizing Fractures
• Integration of Numerical and Semi-quantitative Data	**Reservoir Heterogeneity**
• Field-Scale Stratigraphic Sequence Models	• Low-Cost Performance Prediction Methods
• Lithology and Fluid Prediction from 3-Component Seismic Data	• Rapid Methods for Reservoir Heterogeneity Description
• Measurement of Fluid Saturation behind Pipe	• Basic Fluid Flow Studies in Heterogeneous Systems
• Mobility Control in Heterogeneous Reservoirs	• Physical Models for Simulator Verification
	Individual Research Activities
Resource Assessment	• Near-Well Profile Control and Permeability Modification
• National Assessment of Unrecovered Oil and Gas Resources	• Forward Process Response Geological Models
• Effective Technology Transfer System	• Modeling Multiphase Flow and Inflow Performance
	• Evaluation Methods for Horizontal Wellbores
	• Cement Bond Logging

opment of improved mobility control agents to mitigate heterogeneity effects. Quantification and input of geologic, geophysical, and engineering data into the reservoir simulator are addressed by research on improved methodology to integrate numerical and semiquantitative data and by studies on procedures for averaging reservoir properties.

Description of Research Activities for $10 Million Program

Resource Assessment Evaluation

- Assessment of Unrecovered Oil and Gas Resources
  A comprehensive national resource assessment requires the development of an appropriate methodology using existing data bases to characterize the geographic and geologic distribution of unrecovered hydrocarbons based on geological, engineering, and physical factors, as well as the economic limits that influence recoverability. Determination of the potential unrecovered mobile oil, immobile oil, and untapped gas resources will provide an objective basis for establishing regional research and technology development priorities.

Integrated Reservoir Heterogeneity Category

- Averaging Procedures for Reservoir Simulation
  Averaging procedures seek to incorporate small-scale flow properties into "effective" or scale-adjusted properties for large-scale reservoir simulation blocks. To be done correctly, such procedures must account for all major variables affecting flow.

- Controls of Geologic Heterogeneity on Reservoir Performance
  The impact of geologic heterogeneity on recovery performance can be effectively studied by comparing field production history with geologic characterizations using computer methods.

- Reservoir-Scale Outcrop Investigations
  Outcrops are the only direct source of detailed reservoir-scale information on the lateral variability of reservoir properties. Detailed mapping of depositional and diagenetic facies, rock fabrics, and petrophysical properties on the outcrop will provide data for use in investigations of methods required for scaling permeability as well as other critical reservoir variables.

- 3-D High-Resolution Seismic Mapping
  High-resolution seismic investigations extend the information content in temporal and spatial frequency components of the 3-D seismic method to provide continuous control for mapping interwell reservoir heterogeneity before and during field development.

- Integration of Numerical and Semiquantitative Information
  Interwell patterns of reservoir properties must be characterized in sufficient detail to improve oil recovery. Data available to accomplish this task include both numerical and semiquantitative geologic and geophysical data. This activity encompasses investigations into geostatistic and stochastic methods as a means of integrating semiquantitative reservoir descriptions and numerical data, extrapolating into interwell areas, and inputting data into the reservoir simulator.

- Field-Scale Stratigraphic Sequence Models
  Stratigraphic sequence research is focused on improved methods for integrating well log, core, and seismic data to characterize and catalog depositional systems facies models. The models provide a basis for predicting the distribution and occurrences of the most likely reservoir types associated with various stratigraphic sequence system tracts. Such techniques are required for extension of field limits and evaluation of the potential for production below existing field pays.

- Lithology and Fluid Prediction from Seismic Data
  Considerable information concerning lithology and fluid content can be obtained by observing the relative propagation behavior of various acoustic wave types. These observations can be made by analyzing multicomponent seismic data (that is, components of motion recorded in

three orthogonal directions). The objective of this activity is to develop new methods of processing and analyzing such data to maximize information for describing reservoir heterogeneities.

- Measurement of Fluid Saturation Behind Pipe
  One of the highest priority needs for reservoir evaluation is an improved methodology for reliable determination of various rock-fluid parameters in cased holes. Industry interest and encouragement make continued research in this area a high-priority activity.

- Mobility Control in Heterogeneous Reservoirs
  There is a need to develop better and more cost-effective foams and thickeners for carbon dioxide and other EOR processes to improve displacement efficiency in heterogeneous reservoirs. In particular, agents are needed to perform under adverse reservoir conditions of high temperature and high salinity.

$20 Million Multidisciplinary Program Option

The $20 million program includes the 24 highest ranked Priority-1 research activities (table 7). This program includes and builds on the reservoir heterogeneity effort of the $10 million program and adds an integrated reservoir geomechanics program and several individual-discipline activities. The geomechanics effort supplements a basic understanding of rock mechanics directed toward structural styles, naturally fractured reservoirs, and induced-fracture well treatments. Additional activities are included in the reservoir heterogeneity program that are designed to develop rapid, cost-effective techniques for estimating oil recovery and describing geologic heterogeneity. In addition, the $20 million program includes several single-discipline projects such as basic studies of fluid flow in complex media and physical (CT scan) modeling. New methods to control flow between the wellbore and the formation will be addressed by investigating cement bonding and the use of polymers and gels. Finally, investigations into unique production problems associated with horizontal wellbores are recommended for the $20 million program.

Description of Additional Research Activities for $20 Million Program

Integrated Reservoir Geomechanics Category

- Rock Mechanics and In Situ Stress Characterization
  Two areas offer significant potential for breakthroughs in the geomechanics effort. First, a better understanding of the influence of basic rock mechanics and stress-strain relations in rock formations on the success of artificial fracturing is needed. Second, improved insight is needed into the interaction of fluids and rocks in a propagating fracture and the deformation of the porous-elastic medium. Both require advanced computer simulation and modeling of fracture dynamics.

- Simulation and Modeling Hydraulic Fracturing
  Improved numerical modeling methods, coupled with actual field verification, are a significant area of research. Enhanced recovery from tight formations requires a specially designed fracture program based on innovative modeling techniques.

- Structural Style Models for Reservoir Frameworks
  The research involves the determination of the controls of stress and strain history and related structural style on the nature, orientation, and intensity of deformational features of different reservoir rock types. In addition to laboratory tests on various reservoir rocks, it involves field studies to assess intensity of fractures, small faults, and stylolites as a function of their resultant strain in different rock types and control on reservoir quality.

- Geophysical Methods for Characterizing Fractures
  The shear-wave splitting phenomena that relate to preferential polarizations and

differential velocities of shear waves as they propagate through fractured media provide a potential mapping technique for characterization of fractured reservoirs. In addition, there are many additional opportunities for the application of three-component seismology to recovery research such as mode-converted waves and amplitude versus offset analysis.

Integrated Reservoir Heterogeneity Category: Additional Activities

- Development of Low-Cost Performance Prediction Methods
  Currently, much unrecovered hydrocarbon exists in reservoirs operated or controlled by small oil and gas companies that do not have financial resources to apply expensive recovery methods to their reservoirs. Low-cost methods of predicting reservoir performance would provide a cost-effective avenue for these companies to evaluate available recovery methods and select economically viable programs.

- Rapid, Cost-Effective Methods to Describe Reservoir Heterogeneity
  Geological descriptions are a necessary but time-consuming task in reservoir characterization. This activity would focus on integrating geophysical, logging, and computer techniques as well as other methods for significantly decreasing the time required to determine, both in the laboratory and in the subsurface, the types and distributions of geologic heterogeneities.

- Basic Fluid Flow Studies in Heterogeneous Systems
  Heterogeneity is the basic determinant in fluid distribution and cannot be readily studied in the laboratory because of scaling difficulties between laboratory experiments and field tests. Improved numerical simulation techniques are required for better interpretation of flow regimes and the scale at which they are important.

- Physical Models for Simulator Verification
  Confidence in numerical models arises from their degree of success in predicting physical observations. Recent developments in computerized tomography (using either X-ray or magnetic sources) have shown promise in providing core flow visualization previously unavailable for verifying numerical models.

Individual-Discipline Activities

- Near-Well Profile Control and Permeability Modification
  Variable permeability profiles, whether near-well or in-depth, can sometimes be improved by polymer/gel and precipitation techniques that selectively and beneficially reduce interval fluid flow. The permanence of these treatments and methods for selective placement within the reservoir are of key importance.

- Geologic Forward Process-Response Models
  Improved process-response models are required to establish field reservoir frameworks that control distribution of reservoir quality facies. Field-based studies will provide geologic constraints for model development and tests of model predictions, thus ensuring that model-derived predictions reasonably simulate the real world. Output of models should be in a form suitable for input to reservoir simulators, synthetic seismic profiles, and synthetic wireline logs.

- Modeling Multiphase Flow and Inflow Performance
  Rapid changes take place in the properties of fluids near the wellbore and within completion intervals. Detailed studies of the multiphase behavior of reservoir fluids within and across completion intervals can be useful in improving the production efficiency of completions.

- Evaluation Methods for Horizontal Wellbores
  Successful drilling and completion of horizontal wells have provided a significant new potential for improving recovery from mature reservoirs. Utilizing this new well configuration demands a new research to develop improved techniques for evaluation and completion of horizontal wellbores.

- Cement Bond Logging
  The necessity for a positive seal between the casing and cement and the cement and

formation in isolating zones during well completions requires improved bond log determination and interpretation techniques. This is necessary to provide assurance of isolation following normal primary cement placement and squeeze-cementing operation.

$50 Million Multidisciplinary Program Option

The $50 million program (table 8) includes all 64 Priority-1 research activities. The program includes and builds on the $10 and $20 million programs in addition to including integrated rock/fluid interactions activities, as well as additional reservoir heterogeneity and reservoir geomechanics activities. Several individual discipline research activities are also included in the $50 million program.

The new, integrated research activities added in this program include a focused effort to better define reservoir rock/fluid interactions. Geologic studies of diagenesis that integrate sedimentology, paleohydrology, and geochemistry are aimed at predicting the spatial distribution and controls on diagenetic heterogeneities. The program will provide improved modeling techniques for defining the interaction between the rock minerals and injected fluids, which is required to better understand inflow performance and reservoir modification during production. Statistical analysis of natural fracture distribution, fluid flow in fractures, evaluation of faults as permeability barriers, quantified fault descriptions, and the effect of rock stress on well perforations are included in the reservoir geomechanics program. The reservoir heterogeneity effort is expanded by the addition of research activities focused on well-to-well seismic methods, cataloging reservoir heterogeneity types, new geochemical wireline log techniques, improved understanding of reservoir seals, quantifying facies models, and using production data for predicting remaining reserves. Individual activities are listed by discipline and address research needs related to specific discipline problems.

Description of Additional Research Activities for $50 Million Program

Integrated Rock/Fluid Interaction Category

- EOR Rock/Fluid Interactions Processes
  Physical and chemical interactions of fluids and reservoir rocks are related to the molecular structure of fluid components and mineral composition of reservoir pore surfaces. Modern surface-science analytical techniques must be used to investigate the molecular, ionic, and thermodynamic factors controlling fluid-mineral interactions.

- Modeling Geologic Diagenetic Variability
  Modeling reservoir diagenetic variability can lead to delineating additional stratigraphic traps and to better defining interwell geologic heterogeneity. Studies should be supported that examine diagenetic modification of pore space on the reservoir scale.

- Numerical Modeling of Matrix Acidization
  Acidizing is an effective way to remove near-wellbore damage and increase well productivity. Detailed models of the fundamental acid reaction process will lead to further understanding of this important chemical stimulation technique.

- Interaction between Injected Fluids and Rock Minerals
  Reactions of injected fluids with pore-surface minerals can produce changes in reservoir quality that significantly alter production performance. Improved geochemical and fluid flow modeling techniques are needed to better predict the effect of injected fluids on reservoir quality.

- Near-Wellbore Formation Damage
  Formation damage created during the initial drilling, workover operations, or the production life of a well can drastically affect the recovery efficiency. An improved knowledge of the mechanisms of formation damage and of methods to reduce damage is needed.

Table 8. Additional Research Activities for $50 Million Program.

Integrated Program Efforts	Individual-Discipline Program Activities
Rock/Fluid Systems • EOR Rock/Fluid Interactions Processes • Modeling Geological Diagenetic Variability • Numerical Modeling of Matrix Acidization • Interaction between Injected Fluids and Rock Minerals • Near-Wellbore Formation Damage	**Engineering Program Efforts** • High-Order Convergence Methods of Reservoir Simulation • Numerical Modeling Scale-Up Methods • Miscible/Immiscible Gas Displacement Processes • Monitoring of Laboratory EOR Processes • Perforating Performance Evaluation Techniques • Transient Reservoir Wellbore Interactions • Cement Displacement Mechanisms
Reservoir Heterogeneity • Well-to-Well Seismic Tomography • Quantification of Stratigraphic Facies Models • Catalog of Heterogeneity Styles and Production Response • Use of Production Data to Locate Remaining Hydrocarbons • Physical Characteristics of Reservoir Seals • Rock and Fluid Properties from Well Logs	**Geological Program Efforts** • Inverse Geological Modeling
Reservoir Geomechanics • Fault Reservoir Partitioning • Quantification of Fault/Fracture Descriptions for Simulation • Statistical Characteristics of Fracture Networks • Fluid Flow in Fractured Media • Frac Fluid Behavior • Stress Effect on Perforation Charge Performance	**Geophysical Program Efforts** • Borehole Seismic Methods • Automated Structural and Stratigraphic Interpretation of Seismic Data

Integrated Reservoir Heterogeneity Category: Additional Activities

- Well-to-Well Seismic Tomography
  Well-to-well tomography offers opportunities for high-resolution interwell heterogeneity mapping because of improved data quality provided by one-way travel paths, strong borehole coupling of the source and receiver, and the resultant lower signal attenuation. The field application, special computer processing, and interpretation of tomographic data should be conducted when an effective downhole source and multielement array are available from the geophysical industry.

- Empirical Quantification of Stratigraphic Facies Models
  This research will provide data in three dimensions and within the context of genetic stratigraphy that can be used in facies models to predict reservoir property distributions. The information to be acquired includes spatial frequencies of specific

reservoir facies, geometries, interconnectedness, nature of bounding surfaces, and other permeability barriers within genetic sequences.

- Catalog of Heterogeneity Styles and Production Response
Reservoir characterization studies need to be systematically cataloged by reservoir type within a single folio series. Reservoir architecture and its relationship to production will be a highlight of the catalog, as will techniques and strategies for reservoir description.

- Use of Production Data to Locate Remaining Hydrocarbons
Production history data can be used to predict and describe the distribution of remaining unrecovered hydrocarbons in a reservoir. This activity would provide for development of new methods for modeling and interpretation of production data in terms of the distribution and character of remaining oil and gas reserves.

- Physical Characteristics of Reservoir Seals (Pressure Cells)
Reservoir seals can be characterized in terms of pressure cells. Studies of pressure cells can lead to better understanding of permeability barriers that control subsurface fluid flow, aquifer performance, and compartmentalization of reservoirs.

- Rock and Fluid Geochemical Properties from Well Logs
Well logs are fundamental tools for determining in situ rock and fluid properties. Although a variety of log types are currently available, there is a need for new and improved measurements for interpretation of geochemical properties of reservoirs.

Integrated Reservoir Geomechanics Category: Additional Activities

- Fault Reservoir Partitioning
The focus of this activity would be on investigating and characterizing the effectiveness of reservoir partitioning by intrafield faults as a function of fault type, displacement, and affected lithologies.

- Quantification of Fault/Fracture Descriptions for Simulation
Geologic descriptions must be quantified in a manner that is suitable for reservoir modeling. Methods of quantifying fracture description are needed to test the impact of natural fractures on fluid-flow predictions based on simulation modeling.

- Statistical Characteristics of Fracture Networks
Wellbores contact only a small sample of fractures in a fractured reservoir. Statistical characterization of fracture networks and determination of interconnection of fractures based on outcrop studies can aid in determining fracture porosity distribution in the subsurface.

- Fluid Flow in Fractured Media
Studies are needed to clarify the effects of connate and injected fluids on natural and induced fractures and propants.

- Frac Fluid Behavior
An important subject of research concerns the physical properties, and changes in the properties, of frac fluids during the fracturing process.

- Stress Effect on Perforation Charge Performance
Emphasis of the activity would be on characterizing the effects of formation stress on the performance of perforations created by shaped charges.

Individual-Discipline Activities: Additional Activities

- High-Order Convergence Methods of Reservoir Simulation
Large-scale computations require that approximated flow equations rapidly generate converged solutions. More efficient computation techniques should be developed in the context of various forms of implicitness that will provide improved reservoir simulations at lower costs.

- Numerical Modeling Scale-Up Methods
Scale-ups, such as that for viscous fingering, are among the most important for EOR

but, unfortunately, are the most poorly understood. Different processes are important at different length scales, and it is crucial to understand how they relate to each other.

- Miscible/Immiscible Gas Displacement Processes
  Correlation of process performance in laboratory corefloods with rock/fluid physical properties and interactions can lead to better screening and design procedures for flooding processes.

- Monitoring of Laboratory EOR Processes
  Interpretation of coreflooding experiments for EOR processes is frequently complicated by factors such as viscous fingering, gravity override, and boundary effects. Better methods to interpret and extrapolate corefloods to reservoirs are needed.

- Perforating Performance Evaluation Techniques
  Improved methods are needed to evaluate the actual performance of voidages created by shaped charges in pipe, cement, and formation under actual downhole conditions.

- Transient Reservoir Wellbore Interactions
  Phase inversion and other short-lived, multiphase phenomena occur in the wellbore during well shut-in and start-up. Studies are needed to understand the way these phenomena affect transient well test interpretations.

- Cement Displacement Mechanisms
  Additional detailed work needs to be done to improve the understanding of the way cement slurry fills the space between casing and the wellbore. This improvement may lead to better cementing success.

- Inverse Geologic Modeling
  In order to provide rapid tests of interpretations, improved inverse geologic models techniques need to be developed. Modeling results would provide geologically constrained solutions of interpreted processes responsible for forming observed stratigraphic and structural relationships.

- Borehole Seismic Methods
  Borehole seismic methods, in which the source and/or receivers are in the borehole, provide an opportunity to avoid surface-seismic attenuation and to enhance the information that can be obtained for improved subsurface interwell interpretations.

- Automated Structural and Stratigraphic Interpretation of Seismic Data
  Accurate integration of seismic data with geologic models will provide the basis for significant interdisciplinary advances in the interpretation of field reservoir frameworks and uncontacted reservoir compartments.

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