DOE/BC/14831--19-Vol. 5

VOLUME V

**AN EVALUATION OF KNOWN REMAINING OIL RESOURCES IN PIERCEMENT
SALT DOME RESERVOIRS IN THE GULF OF MEXICO**

Hitesh Mohan*, Mark Rogers*, Alan Becker*, Khosrow Biglarbigi*, Jerry Brashear*

RECEIVED

JUL 28 1998

OSTI

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

*ICF Kaiser - ICF Information Technology, Inc.
9300 Lee Highway
Fairfax, VA 22031-1207

**CLEARED BY
PATENT COUNSEL**

***An Evaluation of
Known Remaining Oil Resources in Piercement
Salt Dome Reservoirs in the Gulf of Mexico***

Prepared for:

***Bartlesville Project Office
Office of Fossil Energy
U.S. Department of Energy
Bartlesville, Oklahoma***

Under Subcontract to:

***Louisiana State University
Department of Petroleum Engineering
Baton Rouge, Louisiana
Contract #DE-AC22-92BC14831***

August 1996

***An Evaluation of
Known Remaining Oil Resources in Piercement
Salt Dome Reservoirs in the Gulf of Mexico***

Prepared for:

*Bartlesville Project Office
Office of Fossil Energy
U.S. Department of Energy
Bartlesville, Oklahoma*

Under Subcontract to:

*Louisiana State University
Department of Petroleum Engineering
Baton Rouge, Louisiana
Contract #DE-AC22-92BC14831*

August 1996

DISCLAIMER

This draft report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

This draft report has not been reviewed by the U.S. Department of Energy, nor has it been approved for application. Approval, when given, does not signify that the contents necessarily reflect the views and policies of the DOE nor does DOE endorse or recommend for use.

DISCLAIMER

**Portions of this document may be illegible
electronic image products. Images are
produced from the best available original
document.**

TABLE OF CONTENTS

	<u>Page</u>
ACKNOWLEDGEMENTS	IV
EXECUTIVE SUMMARY	V
I. OVERVIEW	I-1
A. INTRODUCTION	I-1
B. THE TARGET RESOURCE	I-4
C. ANALYTICAL APPROACH	I-8
D. POTENTIAL FOR BYPASSED AND ATTIC OIL RECOVERY	I-10
E. RECOMMENDATIONS FOR R&D AND TECHNOLOGY TRANSFER	I-13
F. CONCLUSIONS	I-15
II. BACKGROUND AND OBJECTIVES	II-1
A. THE OFFSHORE GULF PETROLEUM RESOURCE: A FEDERAL RESPONSIBILITY	II-1
B. THE OPPORTUNITY FOR THE RECOVERY OF REMAINING OIL RESOURCES IN SALT DOME RESERVOIRS	II-7
C. RECOVERY OF BYPASSED OIL	II-12
D. ATTIC OIL RECOVERY	II-17
E. OBJECTIVES OF THE PRESENT STUDY	II-19
III. BENEFITS OF BYPASSED AND ATTIC OIL RECOVERY	III-1
A. INTRODUCTION	III-1
B. POTENTIAL RESERVE ADDITIONS	III-1
C. ECONOMICS OF BYPASSED AND ATTIC OIL RECOVERY	III-3
D. IMPACT ON NATIONAL ECONOMY	III-5
E. CONCLUSIONS	III-8
IV. APPROACH TO THE ANALYSIS	IV-1
A. INTRODUCTION	IV-1
B. DATA COMPILATION AND PROCESSING	IV-1
C. METHODOLOGY FOR BYPASSED OIL RECOVERY	IV-11
D. METHODOLOGY FOR ATTIC OIL RECOVERY	IV-32
V. RECOMMENDATIONS FOR FUTURE EFFORTS	V-1

LIST OF FIGURES

	<u>Page</u>
I-1 Resource, Reproduction and Reserves in Federal Offshore Gulf of Mexico	I-2
I-2 Increased Abandonment in the Offshore Gulf of Mexico.....	I-3
I-3 Piercement Salt Dome Fields Account for One-Third of the Crude Oil Resources in Federal Offshore Gulf of Mexico.....	I-5
I-4 Attributes of Bypassed Oil	I-7
I-5 Attributes of Attic Oil	I-9
I-6 A) Incremental Oil Reserves from Bypassed and Attic Oil Recovery Processes	I-11
B) Estimated Recovery of Potential Target Resources	
II-1 Offshore Oil and Gas Resources are a Special Federal Responsibility	II-2
II-2 Distribution of Original Oil-in-Place in the Offshore Gulf of Mexico	II-3
II-3 U.S. Offshore Gulf Coast Production and Reserves	II-4
II-4 Increased Abandonment in the Offshore Gulf of Mexico.....	II-6
II-5 Piercement Salt Dome Fields Account for One-Third of Resources in Federal Offshore Gulf of Mexico	II-8
II-6 Salt Intrusions Create Complex Gulf of Mexico Reservoir Structures.....	II-10
II-7 Attributes of Bypassed Oil	II-11
II-8 Attributes of Attic Oil	II-13
II-9 Migrated Seismic Processing Enhances Geological Imaging	II-15
II-10 Migrated Section Before and After Inverseis™ Processing	II-16
II-11 Mechanics of Updip Gas Injection Process	II-18
III-1 A) Incremental Reserves	III-1
B) Number of Economic Projects	
III-2 Recovery of Target Resources	III-4
III-3 Distribution of Direct Federal Revenue between Bypassed and Attic Oil Recoveries.....	III-7
III-4 Imports Avoided as a Result of Bypassed and Attic Oil Recovery	III-9
IV-1 Horizontal Data Collection Form.....	IV-4
IV-2 Well Data Collection Form	IV-5
IV-3 Field Data Collection Form.....	IV-5
IV-4 Definition of Salt Block, Sands & Field	IV-6
IV-5 Coordinates of Map Measurements for Each Fault Block	IV-7
IV-6 Mapped on Analog View of Example Field A.....	IV-8
IV-7 Geometry of the Reservoir	IV-14
IV-8 Grid Layout of Bypassed Model	IV-17
IV-9 Correlation Between Permeability and Porosity	IV-18
IV-10 BOAST Simulated vs. Log Model Results	IV-21
IV-11 Drilling Cost (@ \$30) vs. Depth	IV-24
IV-12 Example 1.....	IV-27
IV-13 Illustration of Possible New Fault Pockets for Example 2	IV-28
IV-14 Decision Tree for Estimating the Potential of the Reservoir in Example 2.....	IV-30
IV-15 General Decision Tree for Estimating the Potential of One-Well Reservoirs	IV-31
IV-16 Grid Layout for the Attic Oil Recovery Model.....	IV-34

LIST OF TABLES

	<u>Page</u>
I-1	Summary of Benefits from Bypassed and Attic Oil Recovery Activities..... I-13
II-1	Selected Updip Gas Injection Projects..... II-18
III-1	Operating Costs and Investments per Barrel of Incremental Bypassed Recovery III-6
III-2	Operating Costs and Investments per Barrel of Incremental Attic Recovery III-6
III-3	Distribution of Direct Federal Revenue between Bypassed and Attic Oil III-7
IV-1	Types of Data Collected for the Present Study IV-2
IV-2	Field Size Distribution of Piercement Salt Dome Reservoirs..... IV-9
IV-3	Fields/Reservoirs Considered for Data Collection IV-10
IV-4	Reasons for Excluding Reservoirs from the Present Study IV-12
IV-5	BOAST Results for Bypassed Oil Recovery..... IV-20
IV-6	Optimum Shut-in time as a Function of Dep Angles IV-34
IV-7	BOAST Results for Attic Oil Recovery IV-35
IV-8	Constants and Coefficients for Various Regression Equations IV-36

ACKNOWLEDGEMENTS

An evaluation of the remaining oil resources in the piercement salt dome reservoirs in the Federal offshore Gulf of Mexico is one in a series of reports of the project on Assistance in the Recovery of Bypassed Oil for Reservoirs in the Gulf of Mexico. The project was funded by the U.S. Department of Energy, Office of Fossil Energy (DOE/FE) under Contract Number DE-AC22-92BC14831. The Louisiana State University (LSU), Department of Petroleum Engineering was the prime contractor for the overall project. ICF Resources Incorporated served as LSU's subcontractor, responsible for the development of an analytical system (models and database) for the characterization and evaluation of the remaining oil resources associated with the piercement salt dome reservoirs.

Mr. Gene Pauling of DOE (previously with Metarie Project Office) served as the Program Manager and Dr. Philip Schenewark of LSU (presently with Rolla University) was the Principal Investigator for the overall project. Mr. Clay Kimbrell of LSU was responsible for the overall project management and providing liaison support among the subcontractors and DOE.

The Minerals Management Service (MMS) of the U.S. Department of Interior (DOI) provided all of the required data for this project. Special recognition is due to Mr. J. Michael Melancon (Chief) for his coordination, guidance, and support of the data collection effort. The supervisors at the MMS, particularly Mr. David Marin, Mr. Michael Pendergast, and Mr. Clark Kinler are recognized for their invaluable technical assistance and support. Mr. Chee Yu (Electronic Data Division) and all other engineers and geologists of the MMS, who answered important technical questions and provided invaluable guidance, are also recognized for their contributions to this very important project.

Special recognition is also due to those who directly performed the work of the project as it relates to the ICF Resources tasks. Dr. Jerry Brashear was the Project Director. Mr. Karl Lang (formerly with ICF Resources) served as the Project Manager through July 1995. Mr. Khosrow Biblarbigi was the Project Manager from August through December 1995. The critical project staff included: Hitesh Mohan (computer modeling), Mark Rogers (Data Collection), Sid Choudhery and Mike Shilkraut (data reduction), David Ribar (decision analysis), and Harold Simms (resource and analytical support). Mr. Alan Becker also provided important consultations on the analytical methodology and Mr. Michael Godec provided valuable comments and guidance in the preparation of the report.

While acknowledging the assistance of all contributors, error of fact, analysis, or interpretation are the responsibility of ICF Resources Incorporated and the Project Director.

EXECUTIVE SUMMARY

The Federal government is responsible for the management and conservation of petroleum resources in the Federal Offshore Gulf of Mexico. The Minerals Management Service (MMS) of the Department of Interior has the most immediate role in assuring diligent development of this very important public resource. The MMS responsibility, however, is limited to making this assurance in the context of prevailing economics and technology. While the "economics" part of the foregoing statement is the operation of the free market, the "technology" part is explicitly subject to potential Federal influence.

The U.S. Department of Energy, Office of Fossil Energy (DOE/FE) has among its missions the facilitation of the development of required technologies to maximize the potential economic recovery of domestic oil and gas resources -- both offshore and onshore, especially from Federal lands. In planning its activities, the DOE/FE relies on a number of comprehensive analytical systems in order to target and prioritize its research and development (R&D) activities and to estimate the benefits of its programs. DOE/FE's analytical system, however, lacks the capability to assess the potential of future technology advances on the exploration, development, and production of crude oil resources in the Federal offshore of the Gulf of Mexico.

The objective of the present effort is to develop an analytical system to characterize a portion of the Gulf offshore resources -- the remaining unrecovered mobile oil resource associated with piercement salt dome reservoirs (hereafter referred to as salt dome reservoirs), and to evaluate additional recovery potential and related economic benefits that could result from the application of improved technologies.

The critical findings of the study include the following:

- The salt dome reservoirs are geologically very complex because of salt dome intrusions, offering a unique challenge in R&D as well as technology transfer.
- The known original oil-in-place (OOIP) for the salt dome reservoirs is estimated at 9.56 billion barrels -- over one-third of the entire resource in Federal Offshore Gulf of Mexico.
- At the conclusion of current recovery operations, about 4.91 billion barrels (51% of OOIP) will remain unrecovered in the salt dome reservoirs. About 1.11 billion barrels of this resource is called unrecovered mobile oil and remains in the reservoirs because of geologic complexity and the limitations it has caused in field development activities. The characterization of the unrecovered mobile oil is the focus of this study. The remaining 3.8

billion barrels is known as immobile oil and is of the target for tertiary oil recovery. The evaluation of this latter resource is beyond the scope of this study.

- Well and platform abandonments, as presently experienced in the Gulf, could limit the economic producibility of the remaining resource. If existing platforms are abandoned, major capital investments will be needed to reacquire the leases, rebuild the infrastructure, and most importantly, drill new wells to regain access to remaining resources.
- The effective transfer and application of existing technology could double the remaining proved reserves associated with the salt dome reservoirs.
- At oil prices in the range of \$16 to \$24/Bbl, the additional reserves are estimated in the range of 557 to 618 million barrels across. The estimated recovery potential in about half of the target resource of 1.11 billion barrels. The recovery potential is also equal to about a third of the remaining proved reserves from the entire resource in the Gulf of Mexico.
- The additional oil recovery activities will also generate significant revenues in terms of royalty payments and taxes to the Federal treasury. From \$2.7 to \$4.6 billion of additional Federal revenues could be collected from the further development and production of these salt dome reservoirs, in the oil price range of \$16/Bbl to \$24/Bbl.
- The additional recovery would also replace imports of foreign oil, keeping between \$9.0 billion to \$18.8 billion in the U.S. economy. This figure is only the direct cost of imports avoided due to increased domestic activity. The true value to the country is actually much higher due to multiplier effects as this money circulates in the U.S. economy, rather than abroad.
- Although the benefits of R&D are not directly measured in this study, because of data and methodological limitations, technology advances could further improve the production and reserves from salt dome reservoirs with even more significant economic benefits to the Federal government and the nation.
- The areas of R&D for the salt dome reservoirs include: directional drilling and completion, 3-D seismic imaging, improved integration of logging and seismic data, development of geologic model for dip prediction, updip gas injection, and environmental protection for offshore operations.
- The R&D and technology transfer objectives could be effectively met through a collaborative effort between the oil industry, universities, local government, as well as the Federal government. Only in this way, the U.S. can benefit from a substantial volume of known remaining oil in the Gulf of Mexico and elsewhere.

As part of the present effort a comprehensive analytical system has been developed for the characterization and evaluation of unrecovered mobile oil associated with the salt dome reservoirs in Federal offshore Gulf of Mexico. The system consists of a comprehensive database containing detailed rock and fluid properties, geologic information, and production and development history for 1,289 major

fields and reservoirs representing an estimated 60% of the salt dome resources in the region. In addition, two separate methodologies and related economic and predictive models have been developed for the evaluation of applicable recovery processes. The system is intended for use as part of DOE's Tertiary Oil Recovery Information System (TORIS).

I. OVERVIEW

A. INTRODUCTION

The Federal government, on behalf of the American people, plays the role of "landlord" for the Gulf of Mexico waters beyond the states' three-mile limit to the outer margin of the continental shelf, up to 200 miles from shore. Optimization of the production and economic values of this national resource is the primary responsibility of Federal authorities. The Minerals Management Service (MMS) of the U.S. Department of Interior (DOI) has the most immediate role in assuring diligent development of the public resource. The MMS responsibility, however, is limited to making this assurance in the context of prevailing economics and technology. While the "economics" part of the foregoing statement is the operation of the free market (OPEC notwithstanding), the "technology" part is *explicitly* subject to potential Federal influence.

The ability of the Gulf of Mexico to continue to provide a substantial portion of domestic energy supplies, however, is in jeopardy:

- **Declining production and reserves.** Gulf of Mexico annual offshore production peaked in 1970 at 350 million barrels and has since fallen by more than 25 percent to a 1994 level of 240 million barrels (Figure I-1). According to the Energy Information Administration (EIA), the remaining reserve is estimated at 1.92 billion barrels, about 6.6% of known original oil in place in the Federal offshore Gulf of Mexico. It is estimated that at the conclusion of the conventional recovery techniques, nearly two-thirds of the known resources will remain unrecovered if cost-effective technologies are not developed and applied to produce them.
- **Increased Abandonment.** By 1970, only 19 platforms had been abandoned and removed from the Federal offshore Gulf. As shown in Figure I-2, the cumulative number of abandoned platforms had reached 1,300 by the end of 1994, and a significant number of additional platforms are expected to have been abandoned in 1995. It is also estimated that about 60% of the remaining oil resources in the Federal offshore have already been abandoned. The reasons for these abandonments are three fold: (1) low oil prices, particularly as experienced from the mid-1980s; (2) maturing offshore fields; and (3) the absence of cost-effective recovery techniques to pursue the remaining oil in place. The current rate of abandonments will have a significant impact on maintaining economic access to the remaining resource for application of future improved recovery techniques.

The U.S. Department of Energy, Office of Fossil Energy (DOE/FE), has among its missions the preservation of access to the known oil and gas resources and enhancement of U.S. oil recovery, both offshore and onshore. In planning its activities, the DOE/FE relies on a number of comprehensive

Figure I-1**Resource, Production and Reserves in Federal Offshore Gulf of Mexico****Distribution of Original Oil-in-Place** **Crude Production (1981-1994)**

Figure I-2
Increased Abandonment in the Offshore Gulf of Mexico

A) Cumulative Platform Abandonments

B) Cumulative Crude Oil Resource Abandonments

analytical systems in order to target and prioritize its R&D activities and to estimate the benefits of its programs. The DOE/FE's analytical system, however, lacks the capability to assess the potential of future technology advances on the exploration, development, and production of crude oil resources in the Gulf of Mexico. As part of a larger effort under contract with the U.S. Department of Energy, Office of Fossil Energy (Contract No. DE-AC22-92BC14831), DOE/FE sponsored the development of an analytical capability to characterize unrecovered mobile oil associated with piercement salt dome reservoirs (hereafter referred to as "salt dome reservoirs") in Federal offshore Gulf of Mexico. Moreover, DOE/FE required evaluation of additional recovery potential and related economic benefits that could result from application of improved technologies in such resources. The salt dome reservoirs were selected by DOE/FE for the following reasons:

- The salt dome reservoirs represent over one-third of the entire resources in Federal offshore Gulf of Mexico
- Geologically, the reservoirs are uniquely complex because of salt dome intrusions. Therefore offering a unique challenge in R&D and technology transfer.

This report focuses on the development of the analytical capability and required evaluation as specified by the DOE/FE.

B. THE TARGET RESOURCE

The salt dome reservoirs represent about one-third of crude oil resources in Federal offshore Gulf of Mexico. The known original oil resource for the salt dome reservoirs is estimated at 9.56 billion barrels (Figure I-3). Of this known resource, 4.05 billion barrels (47%) have been produced to date, and about 600 million barrels (6.2%) represent remaining proved reserves and will be produced by current operations. This will leave 4.9 billion barrels (51%) of known oil unproduced. Of these 4.9 billion barrels, an estimated 3.8 billion barrels represent residual or immobile oil which cannot be displaced by water. The remaining 1.11 billion barrels are believed to be unrecovered mobile oil.

1. Immobile Oil Target

The immobile oil is trapped in the reservoir pores by viscous and capillary forces and cannot be displaced by water. The immobile oil is the target for a number of enhanced oil recovery (EOR) techniques, particularly miscible gas and chemical flooding. In 1983, the DOE Bartlesville Project Office (BPO) conducted a comprehensive assessment of EOR potential in offshore Gulf of Mexico.

Figure I-3

**Piercement Salt Dome Fields Account for One-Third of the Crude Oil Resources in
Federal Offshore Gulf of Mexico**

Source: API 1980, EIA 1994

The study concluded that up to 2.0 billion barrels of additional reserves could be recovered at then prevailing oil prices on the order of \$30/Bbl. It is important to note that the evaluation of immobile oil for the salt dome reservoirs is beyond the scope of the present effort. However, because of the large volume of the immobile oil target, it is strongly suggested that DOE update the 1983 study in order to capture the latest economic reality and the latest technological breakthroughs.

2. Unrecovered Mobile Oil

Mobile oil remains in the salt dome reservoirs after conventional recovery for a variety of reasons. Foremost among them is a uniquely complex reservoir geology. While the salt intrusion created the reservoir structures, it also created complex reservoir segments which have been extremely difficult to image geophysically, and this has a significant impact on the accurate placement of wells in the reservoirs. If wells are not strategically placed in this type of reservoir, segments containing oil with initial saturation could be bypassed and ultimately abandoned if corrective techniques are not adopted. The unrecovered mobile oil associated with salt dome reservoirs consists of three types:

- **Bypassed oil due to inaccurate detection of salt boundary.** As shown in Figure I-4A, the salt intrusions can cause the reservoirs to dip steeply. Exploratory and development drilling activities have tested and developed the flanks of most major salt dome reservoirs. But while oil has been produced from the lower portion of the producing reservoirs, upper parts of the reservoirs may not have been completely drained, potentially leaving behind substantial reserves of trapped oil. This is because accurate seismic imaging around salt intrusions is hampered by refraction of the seismic waves as they enter and exit the salt. Although conventional 2-D seismic techniques are adequate in other geologic settings, this refraction tends to distort the seismic waves around the salt intrusions, making it difficult to determine the dip of the strata and distinguish where the potentially oil-bearing rock formations end and the salt dome begins. Much oil has been bypassed because the salt boundaries were not clearly visible in seismic imaging. If operators could image successfully closer to the salt intrusion, much of this trapped oil could be produced.
- **Bypassed oil due to faulting:** The conventional 2-D seismic technology applied in many of the Gulf of Mexico reservoirs may not have detected all actual faults around the salt domes at the time of original field development in the 1960s and 1970s.

Figure I-4
Attributes of Bypassed Oil

Figure I-4B provides an example of the type of deficiencies with the conventional seismic technology and how it could influence well placement and the volume of bypassed oil. As shown in the example, the 2-D seismic grid intercepts Fault A at points 3, 4, and 5, and Fault C at points 1 and 2, and it does not detect Fault B. This is because of the 2-D seismic line spacing and orientation. As a result, only Faults A and C are mapped by the operator and the two separate blocks are mapped as a single continuous block. The well plans to drain the volume between Fault A and Fault C, but in actuality it will drain only the volume between Fault A and the undetected Fault B. As a result, the oil in the block between Fault B and C remains bypassed. However, with recent development of seismic technology, a 3-D survey could detect Fault B and provide necessary information to properly map the reservoir blocks and identify the bypassed oil.

- **Attic oil:** This oil is trapped against a salt plug or a fault plane updip from the highest well in a reservoir as shown in Figure I-5 A & B. Producing formations on the flanks of salt domes are usually highly faulted and many small reservoirs are formed. Typical characteristics of producing reservoirs on salt dome flanks, like those in offshore Gulf Coast, are steep dips and active water drives. When the oil-water contact advances to the perforated interval in a well, oil left updip is sometimes trapped and cannot be produced. There is little geologic information on the updip portion of the producing zone and an updip well could easily penetrate the salt plug, resulting in a dry hole. The updip gas injection process, however, has offered an alternative technique for the recovery of attic oil with significant successes in offshore Gulf reservoirs. As shown in Figure I-5, injected gas migrates to the upper limit of the producing formation where it intersects the reservoir limit and forms a gas cap. This accumulation of gas displaces oil from the upper portion of the reservoir, forcing it downdip and lowering the oil water contact. Additional oil is produced by both the gas cap expansion and the movement of the oil-water contact back to below the perforations. Some of the injected gas can be recovered and either re-used or sold.

The following section discusses the methodology for the characterization of the unrecovered mobile oil and its future recovery potential.

C. ANALYTICAL APPROACH

As part of the present effort, a comprehensive analytical system has been developed for the characterization and evaluation of unrecovered mobile oil associated with the salt dome reservoirs in Federal offshore Gulf of Mexico. The system consists of a comprehensive database containing detailed rock and fluid properties, geologic information, and production and development history for 1,289 major fields and reservoirs representing an estimated 60% of the salt dome resources in Federal offshore Gulf of Mexico. In addition, two separate methodologies and related economic and predictive models have been developed for the evaluation of bypassed oil (due to faulting) and attic oil resources. Because of severe limitations of data, no methodology could be developed for the characterization of bypassed oil due to inaccurate detection of the salt boundary.

Figure I-5
Attributes of Attic Oil

Based on this new analytical system, the present report provides a comprehensive evaluation of the resource base and its future recovery potential and related economic benefits, based on the following key assumptions and considerations:

- A total of 281 major fields and reservoirs, representing about 14% of the 9.56 billion barrels of original oil-in-place (OOIP), were individually analyzed for their bypassed and attic oil recovery potential. Although data were initially collected for 1,281 reservoirs, more than 1,000 reservoirs were excluded from this analysis because of data inadequacy and deficiency.
- The results presented in this report have been extrapolated from the analyzed resource (281 reservoirs, 1.37 billion OOIP) to the entire salt dome resource (9.56 billion barrels) in Federal offshore Gulf of Mexico.
- This report only evaluates the application of existing technology for the recovery of bypassed and attic oil. Because of data limitations and technical assumptions in the methodology, the benefits of potential future technological advances were not analyzed in this report. However, based on published information, a qualitative description of technology and R&D needs, which are unique to salt dome reservoirs, is provided.
- This report estimates potential benefits at several oil prices ranging from \$16/Bbl to \$30/Bbl, stated in 1995 dollars. All economic analyses reflect the current Federal tax and royalty structures as they relate to offshore oil leases.

All reserve estimates presented in this report are incremental reserves as a result of future bypassed or attic oil recovery projects and they do not include existing proved reserves.

This section summarizes the results of the evaluation in terms of incremental reserves, benefits to Federal treasury and the impact on the national economy.

D. POTENTIAL FOR BYPASSED AND ATTIC OIL RECOVERY

The application of existing technology has the potential of doubling the remaining proved reserves associated with the salt dome reservoirs in the Federal offshore Gulf of Mexico. As shown in Figure I-6, the potential incremental reserves could range from 557 million barrels at a \$16/Bbl oil price to about 618 million barrels at the higher oil price of \$30/Bbl. The distribution of the estimated reserves

Figure I-6

among the bypassed and attic oil recovery are fairly uniform across the analyzed range of oil prices. Nearly 45% to 48% of the estimated economically recoverable resource is attributed to bypassed oil recovery, with the balance attributed to attic oil recovery.

The estimated bypassed and attic oil recovery potential is nearly half the target resource of 1.11 billion barrels, as shown in Figure I-6. This substantial volume of remaining and recoverable oil clearly provides a major justification for focused R&D and technology transfer programs in order to further advance the existing technologies and to promote the application of existing and future technologies among the operators throughout the Gulf.

As shown in Figure I-6, the bypassed and attic oil recovery potentials are not significantly sensitive to increases in oil price. In the case of attic oil recovery, this is because the process does not require any incremental investments, meaning the existing infrastructure can be used to inject the required volume of gas. In the case of bypassed oil recovery, the insensitivity to oil price is due to the fact that there are large volumes of untapped oil in the economic projects which clearly justify the required investments (i.e., drilling costs for new wells) even at oil prices as low as \$16/Bbl.

The bypassed and attic oil recovery activities will also generate revenues to the Federal treasury through increased royalty payments and Federal taxes (both corporate and individual). The revenue estimates in this study consider only direct revenues from the analyzed recovery activities and exclude any additional indirect benefits from multiplier or "ripple" effects in the local or national economy. As shown in Table I-1, the new oil recovery activities could generate from \$1.1 billion to about \$2.3 billion of net royalty payments to the Federal treasury. The additional direct Federal tax receipts could range from \$1 billion to \$3.5 billion across the analyzed oil prices. The total direct Federal revenues (sum of tax receipts and royalty payments) could range from \$2.7 billion at a \$16/Bbl oil price to \$5.8 billion at an oil price of \$30/Bbl.

Increased domestic production from the bypassed and attic oil recovery could offset oil imports, a result which could reduce the Federal trade deficit. The value of the oil produced, the product of reserves and their effective oil price, is a simple measure of their value in reducing imports. As shown in Table I-1, this could amount to between \$9.0 to \$18.8 billion across the analyzed oil prices. The additional value of domestically produced oil generates significant direct economic activity as capital spending, profits, royalties, and taxes are circulated through the U.S. economy rather than exported to

buy foreign oil. To the degree multipliers increase the direct benefit estimated, the new oil recovery activities could stimulate over \$50 billion in future benefits to the U.S. economy.

Table I-1
Summary of Benefits Derived from Bypassed and Attic Oil Recovery Activities

Oil Price	Process	Potential Reserves (million Bbl)	Direct Federal Revenues (\$billion)			Imports Avoided (\$billion)
			Royalty	Taxes	Total	
\$16/Bbl	Bypassed Oil	262	0.5	0.8	1.3	4.0
	<u>Attic Oil</u>	<u>295</u>	<u>0.6</u>	<u>0.8</u>	<u>1.4</u>	<u>5.0</u>
	Total	557	1.1	1.6	2.7	9.0
\$20/Bbl	Bypassed Oil	271	0.7	1.1	1.8	5.2
	<u>Attic Oil</u>	<u>313</u>	<u>0.8</u>	<u>1.0</u>	<u>1.8</u>	<u>6.7</u>
	Total	584	1.5	2.1	3.6	11.9
\$24/Bbl	Bypassed Oil	274	0.9	1.4	2.3	6.3
	<u>Attic Oil</u>	<u>319</u>	<u>1.0</u>	<u>1.3</u>	<u>2.3</u>	<u>8.2</u>
	Total	593	1.9	2.7	4.6	14.5
\$30/Bbl	Bypassed Oil	279	1.0	1.8	2.8	8.0
	<u>Attic Oil</u>	<u>339</u>	<u>1.3</u>	<u>1.7</u>	<u>3.0</u>	<u>10.8</u>
	Total	618	2.3	3.5	5.8	18.8

E. RECOMMENDATIONS FOR R&D AND TECHNOLOGY TRANSFER

Although the benefits of R&D are not measured because of the limitations of the analytical methodology adopted, this section discusses the requirements for technology development based on information available through the public literature. As previously discussed, the Federal offshore Gulf reservoirs offer a large remaining oil resource with promising recovery potential. However, that recovery potential is severely threatened by accelerating deterioration and abandonment of offshore platforms and infrastructure, particularly in more mature areas. The salt dome reservoirs, because of the level of the resource they represent, and because of their unique geologic complexity, require special attention.. As voiced by the operators of the salt dome reservoirs, the following is a description of example R&D areas needed in order to maximize the economic producibility of their resources:

- **Economic MWD Pulser System for Directional Drilling.** It is expected that the bypassed oil in salt dome reservoirs will tend to be found in moderate to small compartments. A key factor that could block the recovery of these potential reserves is the high cost of directional drilling and Measurement While Drilling (MWD) surveying equipment. Currently, the hourly cost of the downhole equipment for drilling during the control portion of a well often exceeds the hourly cost of the rig and personnel. The cost of updip directional drilling from an existing well could in many cases reach the cost of the original well. Research is required

to develop a more cost effective MWD system, such as a highly optimized expendable pulser system.

- **Updip Oil and Gas Recovery Processes.** The updip reserves can be targeted through the use of directional well segments to obtain additional up-dip completions next to salt domes. However, it may not be feasible to place a completion at the highest possible point in the reservoir. The shape of the water/oil/gas interfaces near the producing well can still have a significant impact on the ultimate oil and gas recovery of the up-dip completions. Upward coning or cupping of a water front through the oil zone into the pressure sink of the producing well can reduce the efficiency of the completion. Brine clean-up and disposal problems associated with high rate water production also increases operating costs. On the other hand, the formation of inverted cones of gas or oil late in the life of a completion can sometimes extend the life of the well and increase the updip recovery. Novel completion techniques for co-production of water and hydrocarbons are needed for the optimization of the overall production system performance over the period when coning occurs.
- **Improved Integration of Logging and Seismic Data.** The use of available seismic interpretation methods for improved resolution of the sediments near a salt dome has been a major breakthrough. Additional improvements would be expected if subsurface data concerning rock properties (needed for seismic interpretation) could be obtained using logging methods while drilling the new borehole segments.
- **Use of Geologic Models for Dip Prediction.** Research is needed to investigate the use of geologic models to predict the transport and depositional processes, forming parts of detailed time zones within the environments of deposition. This will provide data on sediment type and salt dome growth. Once the sediment types and the sedimentary structures are understood, the syn-sedimentary depositional dip data can be determined. The geological models could be beneficial in predicting the dip of strata near the salt applying the syn-sedimentary and post-sedimentary dip differences obtained from existing wells. These dip prediction methods could supplement the analysis of sand/shale and porosity/permeability trends within the resolution obtained from seismic data.
- **Improved 3-D Display Methods for Geologic, Geophysical, and Reservoir Simulation Results.** Improved graphical display methods for representing the geological structures and the pressures and fluids saturations within these structures would be extremely useful for allowing optimal well placement plans to be developed by the operational engineers and field personnel. One suggestion is the integration of 3-D display software developed for the imaging of medical information with the seismic and reservoir simulation software.
- **Completion Technology.** Research is needed to improve completion methods in highly deviated wellbores. The development of improved completion techniques could reduce the cost of completing highly deviated wells and could potentially increase the recovery of oil and gas from target reservoirs.

- **Environmental Protection in Offshore Drilling and Completion.** Research is needed to mitigate potential environmental problems associated with offshore drilling and production operations. The drilling of highly deviated wellbores is best accomplished using oil-based drilling mud, which must be handled and disposed of in an environmentally safe manner. The production of oil and gas often results in the co-production of large volumes of formation waters which must be processed and disposed of with no potential risk to the environment. Formulating methods of mitigating these potential problems could reduce the costs and risks associated with the proposed drilling and production operations.

A collaborative R&D effort between industry, universities, state and local governments, and the Federal government focused on developing the required technologies and their successful applications in the Federal offshore salt dome reservoirs would benefit the operators, the Federal government, and the nation as a whole. It is important to note that nearly all of the areas for technology advances mentioned above would also be applicable to other resources in the Gulf (i.e., sub-salt and deep water resources).

F. CONCLUSIONS

Piercement salt dome reservoirs account for over one-third of the oil resources in Federal offshore Gulf of Mexico. At the conclusion of conventional recovery techniques, about 4.91 billion barrels, or 51% of known original oil-in-place, will remain an accessible target for future oil recovery processes. While this target is substantial, it unfortunately will not remain a target indefinitely. Increased levels of platform and infrastructure abandonments have already limited economic access to a significant portion of this important resource.

This analysis concludes that the effective transfer and application of the existing technology could double the proved reserves in the Federal offshore salt dome reservoirs in the Gulf of Mexico. The incremental reserves could range from 557 to 618 million barrels at oil prices of \$16/Bbl to \$30/Bbl. The estimated reserves are equal to over one-third of the entire proved reserves in Federal offshore Gulf of Mexico. These additional reserves could also generate significant direct revenues to the Federal treasury and substantial direct and indirect benefits to the national economy.

Technology advances could further increase the production and reserves from salt dome reservoirs with even more significant economic benefits to the Federal government and the nation. Although the benefits of R&D are not directly measured in this analysis, areas of R&D and technology transfer have been identified which are unique to the salt dome reservoirs.

Examples of such R&D areas include:

- Directional drilling and completion
- 3-D seismic imaging
- Updip oil and gas recovery processes
- Improved integration of logging and seismic data
- Use of geologic model for dip prediction
- Addressing environmental issues associated with offshore operations.

The R&D and technology transfer objectives could be effectively met through a collaborative effort between industry, universities, local governments, and the Federal government. Only in this way, can the U.S. benefit from a substantial volume of known remaining oil in the Gulf of Mexico.

II. BACKGROUND AND OBJECTIVES

A. THE OFFSHORE GULF PETROLEUM RESOURCE: A FEDERAL RESPONSIBILITY

The Federal petroleum resource in the Gulf of Mexico is located beyond the states' three mile limit to the outer margin of the continental shelf, up to 200 miles from shore (Figure II-1). The known original oil resource lying beneath Federal waters in the Gulf of Mexico is estimated to total 29.17 billion barrels (Figure II-2). While additional exploration will add to this total, the significant volume of the currently discovered resource alone argues for careful consideration of the means to maximize its recovery. Federal royalties and taxes, and U.S. economic activity, energy security, and balance of payments, can all benefit from producing more of this resource than is currently expected based on existing available technology. According to the EIA, of the known original oil resource in Gulf of Mexico reservoirs, 9.94 billion barrels (34%) have been produced, and 1.92 billion (6.6%) will be produced by technology currently in place. Currently developed technology then, will leave almost 17 billion barrels (60%) of known oil unproduced. Offshore resources in the Gulf of Mexico, however, face severe problems including declining production and reserves an accelerating rate of platform abandonment, and accelerating resource abandonment of the remaining of oil resource.

1. Declining Production and Reserves

In the Gulf of Mexico, annual offshore production peaked in 1970 at 350 million barrels and had since fallen by more than 37 percent to a 1990 level of 220 million barrels (Figure II-3). Over the next three years, annual production increased slightly to 255 million barrels by 1993. The published data indicate, once again, a decline in production to about 245 million barrels in 1994, the last year for which published data are available.

In 1981, Gulf of Mexico Federal offshore oil reserves totaled 1.85 billion barrels (Figure II-3). Subsequently, the reserves decreased by more than 19 percent to a 1987 level of 1.5 billion barrels. Between 1988 and 1994, reserves have increased to about 1.9 billion barrels. Although the increases in production and reserves are caused by new field and reservoir discoveries in the offshore Gulf area, it is important to emphasize that both production and reserves from previously discovered fields and reservoirs are declining rapidly, with significant increases in resource and platform abandonment, as described in the following section.

Figure II-1
Offshore Oil and Gas Resources are a Special Federal Responsibility

Figure II-2

Distribution of Original Oil-in-Place in the Offshore Gulf of Mexico

Source: API 1980, EIA 1994

Figure II-3
U.S Offshore Gulf Coast Production and Reserves
A) Production (1981-1994)

B) Reserves (1981-1994)

2. Increased Platform and Resource Abandonment

By 1970, only 19 platforms had been abandoned and removed in the offshore Gulf of Mexico. Over the next 25 years, however, the number of abandoned platforms increased significantly. As shown in Figure II-4, the cumulative number of structures removed from the offshore Gulf of Mexico has reached over 1,300 by the end of 1994, and a significant number of additional platforms, although not yet published, are expected to have been abandoned in 1995. Cumulatively, well over 30% of the remaining oil in the offshore Gulf had been abandoned by 1990, the last year for which such data are available (Figure II-4). An additional 18% of crude oil resources were also reported as inactive leases which were in imminent danger of abandonment. Therefore, by 1991 the total remaining oil resource, either abandoned or inactive, had reached an alarming 50%. If historical trends hold true, the total resource abandonment in offshore Gulf coast could be estimated at about 60% by the end of 1995. Given the rapid and accelerating rates of the decline in production and reserves as well as increases in rate of platform and resource abandonment (which will render any future application of new technology virtually impossible), the development and application of advanced technologies is critical to develop and produce a significant portion of nearly 13 billion barrels of Gulf of Mexico oil that will otherwise remain unrecovered.

The U.S. Department of Energy, Office of Fossil Energy (DOE/FE), has within its mission the preservation of access to the known oil and gas resources and the enhancement of U.S. oil recovery, both offshore and onshore. DOE/FE relies on a number of comprehensive analytical systems in order to target and prioritize its R&D activities and to estimate the benefits of its programs. As part of a larger effort (Contract Number DE-AC22-92BC14831), DOE/FE sponsored the development of an analytical capability to characterize unrecovered mobile oil associated with piercement salt dome reservoirs (hereafter referred to as the salt dome reservoirs) in Federal offshore Gulf of Mexico, to be able to evaluate the additional recovery potential and related economic benefits that could result from application of improved technologies in such resources. The salt dome reservoirs were selected by DOE/FE for the following reasons.

- The salt dome reservoirs represent over one-third of the entire resources in Federal offshore Gulf of Mexico.
- Geologically, they are uniquely complex because of salt dome intrusions, therefore offering a unique challenge in R&D and technology transfer.

Figure II-4

Increased Abandonment in the Offshore Gulf of Mexico

A) Cumulative Platform Abandonments

B) Cumulative Crude Oil Resource Abandonments

B. THE OPPORTUNITY FOR THE RECOVERY OF REMAINING OIL RESOURCES IN SALT DOME RESERVOIRS

Salt dome reservoirs represent about one-third of the entire resource basin in the Federal offshore Gulf of Mexico. The known original oil resource for the salt dome reservoirs is estimated at 9.56 billion barrels (Figure II-5). Of this known resource, 4.05 billion barrels (47%) have been produced to date and an estimated 600 million barrels (6.2%) represents remaining proved reserves to be produced by current operations. This will leave 4.9 billion barrels (51%) of known oil unproduced; of this, an estimated 3.8 billion barrels represent residual or immobile oil. The remaining 1.11 billion barrels represent unrecovered mobile oil.

1. Immobile Oil Target

The immobile oil is trapped in the reservoir pores by viscous and capillary forces and cannot be displaced by water. The immobile oil in the offshore Gulf coast is the target for a number of enhanced oil recovery (EOR) techniques particularly miscible gas and chemical flooding. While these processes generally require larger investments and higher operating costs than conventional recovery processes, they are capable of producing substantial volumes of incremental oil with significant economic benefits to the nation. In 1983, DOE/BPO conducted a comprehensive assessment of the enhanced oil recovery potential in the offshore Gulf of Mexico (Reference 1). The analysis included a thorough projection of EOR potential under several economic and technical scenarios. The study concluded that up to 2 billion barrels of reserves could be recoverable by applicable EOR techniques at then prevailing oil prices.

It is important to note that the evaluation of the EOR potential for the Federal offshore salt dome reservoirs is beyond the scope of the present effort. However, because of the substantial volume of the immobile oil target, this 1983 study should be updated to capture the latest economic reality and technological breakthroughs. Furthermore, an updated study could consider the potential associated with new fields and reservoirs discovered since 1983. Some of the products of the present effort, particularly the updated database of the Federal offshore reservoirs, could be useful in undertaking such an EOR assessment.

Figure II-5

**Piercement Salt Dome Fields Account for One-Third of Resources in
Federal Offshore Gulf of Mexico**

Source: API 1980, EIA 1994

2. Unrecovered Mobile Oil Target

Mobile oil remains in the salt dome reservoirs after conventional recovery for a variety of reasons. Foremost of these is a uniquely complex reservoir geology. As shown in Figure II-6, many of the Federal offshore Gulf reservoirs are associated with salt domes and complex faulting that occurred near the salt dome. While the salt helped to create the reservoir structures, it also created complex reservoir segments which are extremely difficult to image geophysically and this has a significant impact on the placement of wells in the reservoir. Needless to say, if wells are not strategically placed in this type of reservoir, segments containing oil with initial saturation could be bypassed and ultimately abandoned if corrective techniques are not adopted. The unrecovered mobile oil is of three types:

- **Bypassed oil due to inaccurate detection of salt boundary:** As shown in Figure II-7, the salt intrusions can cause the reservoirs to dip steeply. Exploratory and development drilling activities have tested and developed the flanks of most major salt dome reservoirs. But while oil has been produced from the lower portion of the producing reservoirs, upper parts of the reservoirs may not have been contacted, leaving behind substantial reserves of trapped oil. This is because accurate seismic targeting of drilling around salt intrusions is hampered by refraction of the seismic waves as they enter and exit the salt. Although conventional seismic techniques are adequate in other areas, this refraction tends to distort the seismic images, making it difficult to determine the dip of the strata and distinguish where the potentially oil-bearing rock formations end and the salt dome begins. Much oil has been bypassed because the salt boundaries were not clearly visible in seismic imaging. If operators could explore successfully closer to the salt intrusion, much of this attic oil could be produced.
- **Bypassed oil due to faulting:** The conventional 2-D seismic technology applied in many of the Gulf of Mexico reservoirs may not have detected all actual faults around the salt domes. Figure II-7 provides an example of the type of deficiencies with the conventional seismic technology and it could influence well placement and the volume of bypassed oil. As shown in the example, the 2-D seismic grid intercepts Fault A at points 3, 4, and 5 and Fault C at points 1 and 2 and it does not detect Fault B. This is because of the 2-D seismic line spacing and orientation. As a result, Faults A and B are mapped by the operator as detected and interpreted by the seismic data and the actual two blocks are mapped as a single continuous block. The well is planned to drain the volume between Fault A and Fault C, but in actuality it will drain only the volume between Fault A and the undetected Fault B. As a result, the oil in the block between Fault B and C remain bypassed. However, with recent development of seismic technology, a 3-D survey could detect Fault B and properly map the reservoir blocks and identify the bypassed oil.

Figure II-6
Salt Intrusions Create Complex Gulf of Mexico
Reservoir Structures

Vertical

Horizontal

Figure II-7
Attributes of Bypassed Oil

A

**BYPASSED OIL DUE TO INACCURATE
DETECTION OF SALT BOUNDARY**

B

BYPASSED OIL DUE TO FAULTING

- **Attic oil:** Is the oil trapped against a salt plug or a fault plane updip from the highest well in a reservoir as shown in Figure II-8. As discussed earlier, producing formation on the flanks of salt domes are usually highly faulted and many small reservoirs are formed. Frequently the reservoirs will cover a smaller area than is typically assigned to a single well, resulting in a number of one well reservoirs. Other typical characteristics of producing reservoirs on salt dome flanks, like those in offshore Gulf Coast, are steep dips and active water drives. When the oil-water contact advances to the perforated interval in a well, oil left updip is trapped and cannot be produced. One solution is to drill another well upstructure, but this is risky because there is little geologic control on the updip portion of the producing zone. Moreover, a high well could easily penetrate the salt plug, resulting in a dry hole. The updip gas injection process, however, has offered an alternative technique for the recovery of attic oil with significant successes in offshore Gulf reservoirs.

The following section discusses in detail available and emerging technology for the recovery of bypassed oil and the attic oil from salt dome reservoirs.

C. RECOVERY OF BYPASSED OIL

Very recently two new technological advances have begun to emerge that should be able to substantially overcome past limitations: (1) extremely sensitive seismic interpretation, applicable in salt-prone areas (which previously were very difficult to interpret), has begun to be able to locate oil-bearing, but heretofore undeveloped, reservoirs and reservoir segments; and (2) highly deviated/horizontal drilling that utilizes existing well bores to some depth before drilling to locations that would be uneconomical to drill from the surface. The combination of these technologies, along with advances in the state-of-the-art geological interpretation and engineering simulation technologies, make possible the development of reservoirs that were formerly impossible to image or drill.

Significant advances in seismic processing have been made in the past few years using sophisticated mathematical models and extremely fast, large-memory computers. These advances have made it possible to solve three-dimensional geophysical problems with greater detail and resolution and a higher degree of certainty. Advanced computer processing techniques have been available for a number of years to enhance the images from conventional seismic signals. The ability to mathematically "migrate" a signal has led to improved resolution of the geology at a given location, as shown in Figure II-8.

Figure II-8

Attributes of Attic Oil

Conventional seismic processing has difficulty resolving near vertical features like faults and the corners of fault blocks. These features produce arc-like arrays shown near the base of this conventional seismic section. Conventional seismic can identify simple structures, but more complex structures are poorly defined. "Migration" is a process that calculates (or mathematically migrates) the energy signature from each point along the arc back to the point source that initially produced the signal. With migration, the arcs shown in the conventional seismic section disappear, sharp corners can be resolved, and the faults identified. The migrated seismic image now shows up as a series of blocks having vertical movement along very steep faults.

Migration of seismic signals works well in relatively simple layered situations, as depicted in Figure II-9, but migration does not cope well with complex three-dimensional problems with rapid lateral and/or vertical velocity changes, such as those that are associated with a salt dome. Newer processing programs now being developed, such as Inverseis_{TM}, (Reference 2) that run on large, fast mainframe computers. These new processing programs significantly enhance the seismic section by modeling the course for individual raypaths from the receiver back to the source across vertical, as well as horizontal, refraction interfaces. Existing seismic data may be used, reprocessed, and reinterpreted without additional acquisition costs.

Figure II-10 depicts a typical, conventionally processed and migrated, seismic line across a Gulf Coast salt dome. No great detail is visible and a questionable shadow zone or halo surrounds the edges of the actual salt body. The halo is typical of the problems inherent in data interpretation as discussed by Halbouty (Reference 3). The beds appear to dip away from the structure. Thus, the trapping mechanism for oil and/or natural gas is vague. No reflectors are apparent immediately adjacent to the salt, and there may or may not be oil-charged sandstones present in such an area. The data used to generate the conventional migrated seismic section in Figure II-10 (reprocessed using the Inverseis_{TM} process) shows a much better defined, more accurate, narrow outline for the salt body, and reveals many previously invisible details around the edge, including structural roll-over traps, faults, and untapped attic structures.

Figure II-9

Migrated Seismic Processing Enhances Geological Imaging

Unmigrated Section

Observed phenomenon

Migrated Section

Figure II-10

Migrated Sections Before and After Inverseis_{TM} Processing

CONVENTIONAL MIGRATED SEISMIC SECTION

INVERSEIS_{TM} SEISMIC SECTION

D. ATTIC OIL RECOVERY

In highly dipping reservoirs, which typically occurs around salt domes, field development is typically complicated by the lack of control on the upper limits of the structure. The complication is further increased due to active bottom water drive that exists in the reservoir. In the latter case, much of the updip oil will not have been produced when the highest well in the structure waters out. Updip gas injection process has been found highly successful in many cases in forcing updip oil to migrate down dip where it can be produced by existing wells.

As shown in Figure II-11, injected gas migrates to the upper limit of the producing formation where it intersects a salt plug, fault, or slate barrier and forms an artificial gas cap. This accumulation of gas displaces oil from the upper portion of the reservoir, forcing it downdip and lowering the oil water contact (Reference 4). In the ideal case, enough gas is injected to displace all the oil located above the perforation. However, gas is typically injected in several cycles in order to guard against moving the oil below the original oil-water contact.

The updip gas injection process was first applied by Standard Oil and Gas Company in 1950 (Reference 5). The process was tried in the Camerina "B" sand of West Hackberry field in Cameron Parish, Louisiana. Limited industry acceptance of this recovery process was initially based on this favorable report. A number of additional articles appeared in industry publications and the process was accepted for both one-well and multi-well reservoirs by the mid-1960s (References 6 through 10). Table II-1 presents the description of selected updip gas injection process.

Table II-1
Selected Updip Gas Injection Projects

Company	Field	Location	Project Start Date	Project Result (Incremental Recovery)
Humble Oil Co.	Various*	Offshore and Southern, LA	Late 1950	3.4 million barrels
Tidewater Oil Co.	Venice	Southern, LA	1958	120 thousand barrels
Shell Oil Company	Black Bayou	Offshore, LA	1969-1970	20 million barrels
Chevron Oil Co.	Bay Merchant	Offshore, LA	1967	25 thousand barrels per well
Mobil Oil Co.	Ship Shoal (72)	Offshore, LA	1959-1960	100 thousand barrels per well
Shell Oil Co.	Mississippi Canyon (281)	Offshore, LA	1984	44 thousand barrels per well

*130 projects in various fields

Figure II-11

Mechanics of Updip Gas Injection Process

E. OBJECTIVES OF THE PRESENT STUDY

The objective of the present effort is two fold: 1) to develop an analytical system to characterize and evaluate the unrecovered mobile oil for salt dome reservoirs in the Federal offshore Gulf of Mexico, and 2) to evaluate incremental reserves, public sector revenues, and nationwide economic activities that could result from the recovery of such oil resources in the Gulf area.

As part of this effort, a comprehensive database of major salt dome reservoirs has been developed. The database contains detail rock and fluid properties, geologic information, and production and development history for 1,281 major fields and reservoirs representing an estimated 60% of the total known resource associated with salt dome reservoirs in the offshore Gulf. In addition, two separate methodologies and related economic and predictive models have been developed for the evaluation of bypassed oil (due to faulting) and attic oil resources. Because of severe limitations of available data, no methodology could be developed for the characterization of bypassed oil caused by inaccurate detection of the salt boundary.

Based on these new analytical capabilities, the present report provides a comprehensive evaluation of the resource base and its potential recovery and related economic benefits associated with the application of existing technology. However, because of data limitations and technical assumptions in the methodology, the potential benefits of improved technologies could not be characterized. Analyses presented in this report are conducted over a range of crude oil prices from \$16 to \$30 per barrel (in constant 1995 dollars). This price range encompasses the long-term prices likely to prevail over approximately the next 30 years. The study parameters included in this report are incremental oil reserves, Federal royalty, Federal income tax (both corporate and individual), and contributions to gross domestic product (GDP).

REFERENCES

1. *Enhanced Oil Recovery in the Gulf of Mexico*. 1987. U.S. DOE Document Number DOE/ET/14010-1.
2. Professional Geophysics Incorporated, Houston, Texas -- personal correspondence, 1993.
3. Halbouty, Michael T. *Salt Domes, Gulf Region, United States and Mexico*, Gulf Publishing Company, 1979.
4. W.B. Bleakley 1967. *Chevron's Attic Oil Recovery*. OJG, November 13, 1967.
5. G.D. Combs, et. al., 1971, *Gas Injection for Upstructure Drainage*. Journal of Petroleum Technology.

6. Morrow R.M.E., 1957, *Updip Oil Recovery by Downdip Gas Injection*. Petroleum Engineering, No. 4, B28-32.
7. Broom, J.C., et. al., 1959. *Gas Injection for Attic Oil Recovery*. Petroleum Engineering, No. 2, B19-22.
8. *Attic Cellar Oil is Recovered*. Petroleum Week, April 15, 1960, No. 15, 26-31.
9. Franklin, L.O., et. al., 1961. *Recovering Attic Oil*. OGJ, Vol. 59, Pages 132-134.
10. Von der Poel, et. al., 1957. *Attic Oil*. Paper 919-G presented at SPE 32nd Annual Meeting, Dallas, Texas.

III. BENEFITS OF BYPASSED AND ATTIC OIL RECOVERY

A. INTRODUCTION

This chapter assesses the potential benefits of applying existing technology for the recovery of bypassed and attic oil in the salt dome reservoirs in Federal offshore Gulf of Mexico. The analysis is based on analytical models and databases developed specifically as part of this effort. Some key technical assumptions and considerations regarding the analysis include the following:

- A total of 280 major fields and reservoirs representing about 14% of the estimated 9.56 billion barrels of original-oil-in-place (OOIP) were individually analyzed for their bypassed and attic oil recovery potential. Although data were initially collected for 1,281 reservoirs, about 1,000 reservoirs were excluded from this analysis because of insufficient data.
- The results presented in this report have been extrapolated from the analyzed resource (280 reservoirs, 1.33 billion OOIP) to the entire resource (9.56 billion barrels) in Federal offshore Gulf of Mexico.
- This report only evaluates the application of existing technology for the recovery of bypassed and attic oil. Because of data limitations, the benefits of the R & D could not be characterized as part of this report.
- This report evaluates all benefits at several oil prices ranging from \$16/Bbl to \$30/Bbl (in 1995 dollars). All economic analyses reflect the current Federal tax and royalty structures as they relate to offshore oil leases.
- All reserve estimates presented in this report are additional reserves as a result of future bypassed or attic oil recovery prospects and they do not include the existing proven reserves.

This section summarizes the results of the evaluation in terms of incremental reserves, economics of producing such reserves, benefits to Federal treasury, as well as the impact on the national economy.

B. POTENTIAL RESERVE ADDITIONS

The application of existing technology of bypassed and attic oil recovery in the Federal offshore salt dome reservoirs could stimulate a significant amount of reserves with substantial economic benefits over the oil price range analyzed. The recovery techniques could generate from 557 to 618 million barrels of incremental reserves (Figure III-1). These figures are significant because they double the remaining

Figure III-1

proved reserves (as of 1994) and they account for about half of the target resource (1.11 billion barrels of unrecovered mobile oil) in the salt dome reservoirs (Figure III-2).

The distribution of the estimated recovery from bypassed and attic oil recovery are fairly uniform across the analyzed oil prices -- nearly 45% to 48% attributed to bypassed oil recovery, with the balance attributed to attic oil recovery. The potential reserves from bypassed oil recovery ranges from 262 million barrels at the lower oil price of \$16/Bbl to 279 million at the higher oil prices of \$30/Bbl. The reserves attributed to attic oil recovery range from 295 million barrels to 339 million barrels across the analyzed oil prices.

Figure III-1 also shows the total number of economic projects for the analyzed oil prices. The economic projects for the bypassed oil recovery appears to be those with fewer existing wells (typically 9 wells or less). This is because in the presence of a large number of wells, a larger volume of the reservoir block is contacted and potentially all faults are detected; in such reservoirs, the potential for bypassed oil recovery is not significant. The economic projects in the attic oil recovery were mostly those with steep dip angle (above 10°) and with wells located upstructure more than half way toward the salt from the original oil water contact.

C. ECONOMICS OF BYPASSED AND ATTIC OIL RECOVERY

From the perspective of operators, bypassed and attic oil recovery operations (where technically feasible) could generate a significant profit with minimal to moderate investment and operating costs. As expected, the mechanisms of the two recovery processes are quite different, and obviously require different investment and operating costs, as discussed in the following sections:

1. Bypassed Oil Recovery

As shown in Table III-1, the operating costs per barrel of incremental reserves for the bypassed oil recovery ranges from \$1.13/Bbl to \$1.33/Bbl across the analyzed oil prices. The operating cost is primarily the same as the normal operating cost associated with primary production operations in the offshore Gulf of Mexico. The investment costs (both tangible and intangible) per barrel of incremental reserves range from \$2.85/Bbl to \$4.06/Bbl across the analyzed oil prices. The investment costs are

Figure III-2
Recovery of Target Resources

Total OOIP = 9.56 Billion Barrels (BBbl)

primarily associated with drilling and completion costs. The investment cost (per barrel) rises with the oil price because at higher oil prices, less prolific reservoirs become economic and therefore require nearly the same investment for less recovery. Table III-1 also shows the net present value of profit (after tax) per barrel of incremental recovery in the range of \$5.28/Bbl to \$11.22/Bbl across the analyzed oil prices.

2. Attic Oil Recovery

As shown in Table III-2, the operating costs per barrel of incremental reserves range from \$4.90/Bbl to about \$9.70/Bbl across the analyzed oil prices. Much of this operating cost, however, pertains to the purchase and injection of gas and reprocessing and handling the produced gas once the oil production resumes. In this analysis, it is assumed that existing infrastructure (i.e., compressors, treaters) is used and no additional investment is required. The process also appears potentially to be highly profitable -- generating net profits in the range of \$4.96 to \$9.13 per barrel of incremental recovery across the analyzed oil prices.

D. **IMPACT ON NATIONAL ECONOMY**

The application of existing technology in bypassed and attic oil recovery could have a substantial benefit to Federal treasury and the national economy. The benefits to the Federal treasury are measured in terms of additional royalty payments and direct Federal taxes associated with the incremental recovery -- both corporate and individual. The impact on national economy is measured as contributions to gross domestic products (GDP) or the level of imports avoided. The revenue estimates in this report consider only direct revenues from the analyzed recovery activities and exclude any additional indirect benefits from multiplier or ripple effects in the economy.

As shown in Figure III-3, the direct Federal revenues range from \$2.7 to \$5.8 billion across the analyzed oil prices. The contributions of the bypassed and attic oil activities to the direct Federal revenues are fairly uniform across the analyzed oil prices -- 48% to 50% attributed to bypassed oil recovery and the balance attributed to attic oil recovery.

Table III-1
Operating Costs and Investments per Barrel of Incremental Bypassed Recovery

Item	Oil Price (\$/Bbl)			
	16	20	24	30
Incremental Reserves (MMBbl)	262	271	274	279
Total Operating Cost (Million\$)	297	325	343	370
Operating Cost per Bbl (\$/Bbl)	1.13	1.20	1.25	1.33
Total Investment (Million\$)	748	902	981	1,133
Investment per Barrel (\$/Bbl)	2.85	3.33	3.59	4.06
NPV After-Tax Profit (Million\$)	1,384	1,874	2,373	3,131
NPV per Barrel (\$/Bbl)	5.28	6.91	8.67	11.22

Table III-2
Operating Costs and Investments per Barrel of Incremental Attic Recovery

Item	Oil Price (\$/Bbl)			
	16	20	24	30
Incremental Reserves (MMBbl)	295	313	319	339
Total Operating Cost (Million\$)	1,445	1,985	2,368	3,285
Operating Cost per Bbl (\$/Bbl)	4.90	6.34	7.43	9.70
Total Investment (Million\$)	0	0	0	0
Investment per Barrel (\$/Bbl)	0.00	0.00	0.00	0.00
NPV After-Tax Profit (Million\$)	1,464	1,921	2,386	3,091
NPV per Barrel (\$/Bbl)	4.96	6.13	7.48	9.13

Figure III-3

The distribution of incremental Federal revenues among its components (royalty payments and tax receipts) is shown in Table III-3. The royalty payments range from \$1.1 to \$2.3 billion and the tax receipts range from \$1.6 to about \$3.5 billion across the analyzed oil prices.

Increased domestic production from the bypassed and attic oil recovery could offset oil imports, a result which could reduce the U.S. trade deficit. The value of the oil produced, the product of reserves and their effective oil price, is a simple measure of their value in reducing imports. As shown in Figure III-4, this figure could total between \$9.0 to \$18.8 billion across the analyzed oil prices. The additional value of domestically produced oil generates significant direct economic activity as capital spending, profits, royalties, and taxes are circulated through the U.S. economy rather than exported to buy foreign oil.

Table III-3
Distribution of Direct Federal Revenue between Bypassed and Attic Oil Recoveries

Oil Price	Federal	Federal	Total Federal
(\$/Bbl)	Royalties	Taxes *	Revenue
	(Billion\$)	(Billion\$)	(Billion\$)
16	1.1	1.6	2.7
20	1.5	2.1	3.6
24	1.9	2.7	4.6
30	2.3	3.5	5.8

*Includes Personal and Corporate Federal Taxes

E. CONCLUSIONS

The piercement salt dome reservoirs account for over one-third of the entire oil resource base in the Federal offshore Gulf of Mexico. At the conclusion of conventional recovery techniques, about 4.91 billion barrels or 51% of known original oil-in-place, will remain as a target for future oil recovery processes. While this target is substantial, it unfortunately will not remain a target indefinitely. Increased levels of platform and infrastructure abandonments have already limited economic access to a significant portion of this important resource.

This analysis concludes that the effective transfer and application of the existing technology could double the proved reserves in the Federal offshore salt dome reservoirs in the Gulf of Mexico. The incremental reserves could range from 557 to 638 million barrels at oil prices of \$16/Bbl to \$30/Bbl..

Figure III-4
Imports Avoided as a Result of Bypassed and Attic Oil Recovery

These additional reserves could also generate significant direct revenues to the Federal treasury and substantial direct and indirect benefits to the national economy

Technology advances could further improve the production and reserves from salt dome reservoirs with even more significant economic benefits to the Federal government and the nation. Although the benefits of R&D are not directly measured in this analysis, areas of R&D and technology transfer have been identified which are unique to the salt dome reservoirs. Examples of such R&D areas include:

- Directional drilling and completion
- 3-D seismic imaging
- Updip oil and gas recovery processes
- Improved integration of logging and seismic data
- Use of geologic model for dip prediction
- Addressing environmental issues for offshore operations

The R&D and technology transfer objectives could be effectively met through a collaborative effort between industry, universities, local governments, and the Federal government. Only in this way, can the U.S. benefit from the substantial volume of known remaining oil in the Gulf of Mexico.

IV. APPROACH TO THE ANALYSIS

A. INTRODUCTION

The analysis presented in this report is based on analytical models and databases developed specifically for this study. The development work included: data collection and processing, compilation, and development of two separate methodologies and related economic and predictive models for the evaluation of attic oil and bypassed oil resources. The new analytical models and databases are consistent in principle with those available through the Department of Energy's Tertiary Oil Recovery Information System (TORIS). The latter system was developed for the 1984 National Petroleum Council (NPC) analysis of the potential for enhanced oil recovery (EOR) in the U.S. In recent years, the system has been significantly expanded to include evaluation of unrecovered mobile oil (UMO) resources. Prior to the present effort, TORIS did not have any capabilities for evaluation of offshore reservoirs, particularly those associated with salt domes. The databases and models developed as part of this effort will enable TORIS to evaluate the latter resource.

The following section discusses in greater detail the scope, methodology, and rationale for the analytical system developed as part of this effort.

B. DATA COMPILATION AND PROCESSING

The types of data that were collected for the present study fall into four broad categories: reservoir data, reservoir production data, map data, and well data. Table IV-1 presents the specific data elements that were collected in each category. The data were compiled from the sources available through the Department of Interior, Minerals Management Service (DOI/MMS). The specific sources of data from the MMS files include the following:

- **Field and Reservoir Reserves Estimates (FRRE) Database.** This database contains geologic and engineering parameters used to estimate in-place and recoverable oil and gas reserves at the reservoir level. The FRRE data were originally based upon the input from operators and various studies by the MMS, and it is updated regularly.

Table IV-1
Types of Data Collected for the Present Study

1. Reservoir Data

Initial Pressure (PSIA)*
 Temperature (°R)*
 Porosity (avg)*
 Initial Water Saturation (avg)*
 Reservoir Type*
 Number of Penetrating Wells*
 Datum Depth*
 Current Pressure*
 Permeability
 Oil/Water Contact (SS)
 Contact Code (measured, estimated)
 Oil Gravity*
 Oil formation Volume Factor*
 Rock Compressibility*
 Bubble Point Pressure
 Gas in Solution*
 Enhanced Recovery Code (WF, Attic
 Oil, CO₂, etc.)
 Types of Injectants, Volumes
 Start Date on EOR
 Project Life
 Estimated Incremental Recovery
 Area Acres*
 Bulk Volume (Ac-Ft)*
 OOIP (STB)
 Recovery Factor (%)
 R_p (MCF/STB)*
 Recoverable Oil (STB)
 Recoverable Solution Gas (MCF)*

If an Associated Gas Cap is Present:

Gas/Oil Contact (SS)
 Contact Code (measure, estimated)
 Gas Gravity
 Formation Temperature
 Initial Pressure
 Gas Compressibility Factor
 B_{gi} (SCF/CF)
 Evaluation Method
 Acres (Acres)
 Bulk Volume (Ac-Ft)
 Gas in Place (Mcf)
 Recovery Factor (%)
 R_p (Mcf/STB)
 Rec. Gas (Mcf)
 Rec. Cond. (STB)

2. Reservoir Production Data

Annual Oil, Gas, Water Volumes
 Cumulative Prod.*
 Initial Production Date
 Annual Pressures

3. Map Data

Oil Area (Acres)
 Oil Volume (AF)
 Gas Volume (AF)
 Oil area undip of highest penetration in
 oil zone (Acres)
 Oil volume undip of highest penetration
 in oil zone (AF)
 Dip (near Salt, Far from Salt)
 Candidate for Attic Oil Recovery
 (Yes, No, Possibly)
 Geometric Measurements of Fault
 Block Shape

4. Well Data

Well Name
 Sand Top (SS)
 Sand Base (SS)
 Status (Producing, Off Production,
 Abandoned)
 Perf. Intervals
 Core Analysis
 Total Depth (MD)
 Total Depth (SS)

Geologic Age*
 Drive Mech.*

Note:*--Available in the FRRE Database

- **The Maximum Efficient Rate (MER) Database.** This database contains geologic and engineering parameters necessary to estimate the maximum sustainable daily oil and gas withdrawal rate from a reservoir which will permit economic development and depletion of that reservoir without detriment to ultimate recovery. The data are supplied by the operator and includes reservoir data and may include map data.
- **The Maximum Production Rate (MPR) Database.** This database contains geologic and engineering parameters required to calculate the approved maximum daily rate at which oil may be produced from a specified oil well completion or the maximum approved daily rate at which gas may be produced from a specified gas well completion. This data is supplied by the operator and includes reservoir data. The data that were collected from this source is incorporated into the production/injection database which includes all production from all completions of each well in each field on a monthly basis. The data includes completion data and oil, gas, and water production.
- **Geologic Maps.** Maps that were in the MMS files varied in quantity, quality, vintage, and age. Older fields and reservoirs were more fully documented, but these fields were delineated with older methodologies (i.e., 1-D and 2-D Seismic, and well tops). Newer maps were submitted only to the MMS as required for new MERs. There are few, if any, maps past 1988 when it was no longer required to submit maps with MER requests. The only time that maps are required is when there is a new field development. New wells are hand plotted by the MMS staff. The new well data comes into the engineer who has responsibility for the area. The engineer then enters the data for the well, location coordinates and perforations into the production database, but the maps are not always updated.
- **Production/Injection Database.** This database was obtained from the MMS via tape. This database includes the information on a monthly well basis for injection volumes, production volumes, well counts and whether a well or completion is active, shut-in or plugged. Data from this database were used by several of the other databases and many of the internal MMS reports.

In order to assure the consistency and efficiency of the data collection process, several data collection forms were designed and implemented as shown on Figures IV-1 through IV-3.

1. Definition of Fault Block

For the purpose of this study, the following definitions are in effect (Figure IV-4). A *field* is defined by MMS -- typically, a piercement salt dome field has a central core of salt, sometimes with a shale collar. Each *sand* is a planar body that surrounds the core and has a constant dip within. A *block* is a distinct reservoir package which is separated from the surrounding blocks by faults and vertically by a sealing formation.

Figure IV-1
Horizontal Data Collection Form
(used for MER data)

Field _____ Date Collected _____ Initials _____
 No. Fault Blocks _____ Total OOIP _____
 Cum Prod: Oil _____ Gas _____ Water _____ Date _____
 Avg Thickness _____ Avg Dip _____

RESERVOIR DATA

Reservoir Name _____ Field _____ Horizon _____
 Dip: NS _____ FS _____ SF _____ Up Dip Limit _____
 Reservoir Geometry: X1 _____ X2 _____ Y _____
 Area Planimeter _____ Calculated _____
 OOIP _____ Recoverable Reserves _____

<u>Data</u>	<u>Unit</u>	<u>Value</u>	<u>Data</u>	<u>Unit</u>	<u>Value</u>
OOIP	MMStb	_____	OWC	ft ss	_____
porosity	%	_____	OWC d		_____
Swi	%	_____	avg depth	ft ss	_____
Sgi	%	_____	red res	MMstb	_____
Soi	%	_____	eval meth		_____
net pay	ft	_____	cum prod	oil	_____
Boi	RB/stb	_____		water	_____
oil gravity	°API	_____		gas	_____
Rsi	scf/Bbl	_____	cum prod		_____
perm	md	_____	No penetrating wells	°F	_____
Sor	%	_____	Tr	psi	_____
Pi	psi	_____	Pcur		_____

[illegible]

Field _____ Date Collected _____ Initials _____

Discovery Date _____ Location _____

Water Depth: max _____ min _____

CUM Prod: Oil _____ Gas _____ Water _____ Date _____

Operator(s) _____

Total OOIP _____ Horizons _____ Reservoirs _____

Total Wells _____ Producing Wells _____ Date _____

Estimated Ultimate Recovery: Oil _____ Gas _____ Date _____

Salt Shape _____ Salt Province _____

Salt Dim: Max R _____ Min R _____ Depth to Salt _____

NOTES

Figure IV-4
Definition of Salt Block, Sands & Field

2. Map Measurements

For each block in the study, the following parameters were measured from available maps: area, radius of the salt, total radius of the block (to lowest known oil or the oil water contact), the angle subtended by the block, the angle from the right hand edge of the block to each well, and the distance from the front of the block to the well. The dip of the block was calculated by averaging the dip at several wells.

The area of the block was the key parameter in building the block analog. An analog was constructed of the block with the same area as the block, and the front and back sides of the block were kept close to the original block. The analog block was placed over the original block and the well angles were measured. Originally, this was done by hand using a planimeter and protractor. After a number of the blocks were measured, it was possible to digitize the blocks and perform the measurements on a computer controlled digitizer. The information that was collected in both of these manners gives the well and block data relative to the center of the salt and the right hand side of the block. There was no

measurement or preservation of the actual latitude-longitude coordinates of the data. Figure IV-5 shows the relative coordinates and directions of the measurements.

Figure IV-5
Coordinates of Map Measurement for Each Fault Block

Figure IV-6 shows a reservoir block taken from an actual map: block Alpha in an example Field A with wells A1, A2, A3, and A4. Updip is the salt core with a sediment-salt interface where the sand is at its most shallow - 7800 ft. The block shows a nearly uniform dip of 78 degrees, dropping 1,900 feet over the 400 feet from the front of the block to the oil-water contact. The model of the block now has a radial side fault, a front boundary defined by the salt radius and a back radial boundary defined by the oil-water contact. The area is still the same which is essential if one wishes to calculate volumes and areas drained by a well. The salt radius is 300 feet, the total radius to the back of the block is 700 feet. The total angle that the block subtends is 30 degrees. When the wells were measured from the original right side of the block, they were measured at 22, 27, 12 and 33 degrees. One of the wells is now outside of the modeled

Mapped on Analog View of Example Field A

Figure IV-6

block. In the database, it is brought into the block at the edge, while preserving its distance from the front of the block. This correction would also have been made had the well plotted to the right of the right-hand edge of the block. In some cases, wells plot above or below the model block boundaries. These wells were moved in the model to the upper or lower boundary while preserving their radial angles.

3. Field/Reservoir Selection for Analysis

The best completed data sets were those that represented the 60% of the OOIP and those groups were the target of the data collection for this analysis (Table IV-2). For this group of reservoirs all available data were collected, including maps, MER data, and FRRE data. The average block size for this population is 165 acres. This group is represented by 46 fields out of the original 74 fields. As shown in Table IV-2, the remaining 4,520 (the balance between 60% and 100% of OOIP) reservoirs were much smaller and therefore excluded from the analysis because of time and resource limitations.

Table IV-2
Field Size Distribution of Piercement Salt Dome Reservoirs

Number of Fields	Number of Sands	Number of Reservoir Blocks	MM BBL OOIP	Percent OOIP
74	1818	5809	9869	100%
65	751	3553	8659	90%
57	473	2628	7702	80%
46	208	1289	5779	60%

The data were collected for 1,289 reservoirs which represents an estimated 60% of the OOIP in 46 fields as shown in Table IV-3. Some of the maps that were collected could not be utilized because of scale problem, unreadability, and poor quality. Initially, a large percentage of the maps were traced manually. Later in the project, permission was received to photocopy some of the maps. The PL020, SS253, SS291, VR164, and SM009 fields were without maps and reduced the number of available reservoirs to 1,152 reservoirs. FRRE data for 72 fields and MER data for 46 fields were collected even in the absence of maps.

Table IV-3
Fields/Reservoirs Considered for Data Collection
Piercement Salt Dome Fields

	Field Name	Number Sands	Number of Reservoirs	OOIP (Bbl)
1	BM002	21	88	793,092,860
2	EC271	2	5	30,577,991
3	EC338	4	18	66,658,321
4	EI032	2	8	51,991,252
5	EI126	4	43	85,560,605
6	EI128	2	16	44,440,093
7	EI172	1	2	12,789,542
8	EI175	2	6	45,429,331
9	EI188	3	27	61,550,898
10	EI208	4	39	71,548,358
11	EI238	5	10	99,076,647
12	EI276	4	13	74,812,431
13	GI016	10	79	369,683,114
14	MC281	6	33	213,898,719
15	MP041	10	28	583,871,503
16	MP073	1	19	14,842,863
17	MP144	4	5	88,545,000
18	MP290	2	12	36,682,826
19	MP299	5	29	117,641,621
20	MP306	5	67	132,480,357
21	PL020	1	7	11,610,756
22	SM006	2	18	25,804,793
23	SM009	1	4	10,994,294
24	SM073	4	23	102,029,095
25	SM130	5	69	233,141,794
26	SP027	9	48	165,721,249
27	SP061	11	130	283,890,467
28	SP062	5	29	121,918,269
29	SP089	6	24	225,520,890
30	SS113	3	23	46,430,375
31	SS154	2	7	38,684,771
32	SS204	6	61	122,003,998
33	SS208	6	65	220,553,954
34	SS230	2	22	35,605,528
35	SS253	1	4	11,211,206
36	SS274	3	14	61,198,259
37	SS291	2	3	54,523,642
38	ST054	2	9	45,768,261
39	ST135	6	39	115,114,571
40	ST176	2	8	54,846,346
41	ST301	2	14	32,533,794
42	VR164	1	4	16,365,565
43	VR245	3	17	78,478,423
44	VR369	1	4	10,911,714
45	WD030	24	95	601,079,243
46	WD133	1	1	18,050,832
	Total	208	1289	5,779,367,423

The maps were digitized both manually and electronically in relative coordinates using a planimeter and a digitizing table. At the same time, the FRRE database and Production databases were acquired from the MMS. The names of the reservoirs were matched against those from the databases. Approximately 70 reservoirs were not matched, and additional work recovered 67 of these. Some reservoir data from the FRRE database show information for separate reservoirs, but the maps show these as a single reservoir. An effort was made to group the data to match the maps. Even so, not all of the map data matches the FRRE data as the map data and the FRRE data are from different points in time.

When final corrections were made to the merged datasets, (names of reservoirs), the number of useable reservoirs was reduced to 780 reservoirs. This included redigitizing some reservoirs, and checking and correcting typographical errors in reservoir names. Map names such as 8300 A were reported as 8300RA in the FRRE database. By close examinations, most of these problems were fixed.

For a large number of reservoirs, there were problems with well names. The mapped well names did not match the FRRE well names in 184 reservoirs. (It is important to note that the maps are updated by the geologists on an as needed basis and the wells in the database are updated by the reservoir engineers separately). Once again, a best effort was made to make the correlations between the two datasets.

The remaining 596 reservoirs were eliminated because of discrepancies between the number of mapped wells and the number of wells in the production database. The balance, 312 reservoirs was further reduced again by reservoirs in which wells were drilled after 1980, when the maps were no longer updated by the operators. This lowers the count to 281 suitable reservoirs for the study, representing about 14% of the OOIP for salt dome resources in the Gulf of Mexico (Table IV-4).

C. METHODOLOGY FOR BYPASSED OIL RECOVERY

1. Introduction

One of the major goals of this project was to identify the bypassed oil in the salt dome reservoirs. As discussed in Chapter 2 of this report, 3-D seismic data have shown there can be more fault blocks in the salt dome reservoirs than are mapped using conventional 2-D seismic. This lead to the theory that some of the oil which was initially assumed to be in contact with the producing wells is actually bypassed oil which is trapped in the fault blocks that were not mapped at the time of field development

(late 1960s-early 1970s). An effort is made to quantify the bypassed oil and predict its economic recovery potential.

Table IV-4
Reasons for Excluding Reservoirs from the Present Study
Piercement Salt Dome Reservoirs

Number of Fields	Number of Sands	Number of Reservoir Blocks	MM BBL OOIP	Percent OOIP	Reason for Reduction
74	1818	5809	9869	100%	Excluded for size cut-off
65	751	3553	8659	90%	Excluded for size cut-off
57	473	2628	7702	80%	Excluded for size cut-off
46	208	1289	5779	60%	Target of Collection
41		1152			No maps PL020, SS253, VR164, SM009
39		815			Reduced by unuseable maps (no scale, unreadable)
		780			No match reservoir names
		596	3226	34%	No match well names maps to db well names
28		312	1758	18%	No match wells to reservoir db (fewer mapped wells than reservoir db wells)
28		281	1359	14%	Wells drilled after 1980 (not mapped)

2. Methodology

To achieve this goal a methodology was developed which consists of four major steps:

- Quantification of bypassed oil.
- Prediction of potential resource performance.
- Risk analysis to place unmapped fault blocks.
- Prediction of future recovery potential.

In order to quantify the bypassed oil potential, it was necessary to justify the sweep area associated with the historical production of each well. The most efficient way to characterize the sweep area would be to simulate production of each well in a given reservoir using a black oil simulator (VIP, Eclipse, BOAST, etc.). However, this approach was not possible due to difficulties in automating simulation of 1,289 reservoirs using a black oil simulator and the lack of data required to perform a simulation study for each reservoir.

To quantify bypassed oil, it was necessary to predict the recovery efficiency of a reservoir as a function of its properties and well location. The recovery function is defined as:

$$\text{Recovery efficiency} = f(\text{API, Por, Perm, Soi, Dip, Yloc, Xloc, Wcut})$$

where	API	=	API gravity (degrees)
	Por	=	porosity (fraction)
	Perm	=	permeability (md)
	Soi	=	initial oil saturation (fraction)
	Dip	=	dip angle (degrees)
	Yloc	=	location of well relative to reservoir boundary (fraction)
	Xloc	=	location of well relative to water/oil contact (fraction)
	Wcut	=	water cut as of last date of production (fraction)

Prediction of the recovery efficiency function was done using BOAST3-PC for dipping reservoirs. BOAST3-PC was developed by LSU as part of this project to be applied to the simulation of dipping reservoirs.

A recovery efficiency function was developed that can be correlated to the actual cumulative production (to date) for each well in a given reservoir:

$$\text{Recovery Efficiency(RF)} = \frac{\text{Cumulative Production (per well)}}{\text{Oil in Contact of Well (per well)}} \quad \text{--- 1}$$

where,

$$\text{Oil in Contact (per well)} = \frac{7758 * A * h * \phi * S_{oi}}{B_{oi}} \quad \text{--- 2}$$

where	A	= Contact area of the well
	h	= Net Pay (feet)
	ϕ	= Porosity (fraction)
	S_{oi}	= Initial Oil Saturation (fraction)
	B_{oi}	= Initial Formation Volume Factor (Res Bbl/ STB)

Based on the geometry of the reservoir as mapped and discussed in Section A of this chapter, the swept area (A) of a well is calculated as :

$$A = \frac{1}{2}(R_2^2 - R_1^2) \times \beta \quad \text{--- 3}$$

where

R_1 = radius of the water/oil contact from the center of the salt.

R_2 = radius of the salt boundary from the center of the salt.

β = Angle of the Pie in Radians.

Figure IV-7 exhibits the geometry of the reservoir mapped.

Figure IV-7
Geometry of the Reservoir

Substituting values in equation 1, yields:

$$RF = \frac{\text{Cum. Prod.} \times B_{oi}}{7758 \times \left[\frac{1}{2} (R_1^2 - R_2^2) \times \beta \right] \times h \times \phi \times S_{oi}} \quad \text{--- 4}$$

The only unknown in the above equation (4) is the swept angle (β) of the swept area (A). Solving the above equation for the swept angle yields:

$$\beta = \frac{\text{Cum. Prod.} \times B_{oi} \times 43560}{7758 \times \left[\frac{1}{2} (R_1^2 - R_2^2) \right] \times h \times \phi \times S_{oi} \times RF} \quad \text{--- 5}$$

The swept angle (β) defines the oil in contact with each well in terms of its geometry. The only changing parameter in the above equation is the cumulative production of different wells of the reservoir. Thus, the swept angle of any well can be defined as a function of its cumulative production.

Once the swept angle is evaluated for each well in a reservoir, the sum of all swept angles was compared to the total block angle of the reservoir as follows:

$$\text{If } \sum_{i=1}^n \beta_i \geq \text{Total Block Angle} \quad \rightarrow \quad \text{No Bypassed Oil}$$

$$\text{If } \sum_{i=1}^n \beta_i < \text{Total Block Angle} \quad \rightarrow \quad \text{Bypassed Oil Present}$$

To quantify bypassed oil, the difference of the two angles is taken and the amount of bypassed oil is then estimated as

$$\text{Bypassed Oil in Place} = \frac{7758 \times A_b \times h \times \phi \times S_{oi}}{B_{oi}} \quad \text{--- 6}$$

where

$$\text{Area of Bypassed Oil } (A_b) = \frac{1}{2} (R_1^2 - R_2^2) \times \left(\text{Block Angle} - \sum_{i=1}^n \beta \right) \quad \text{--- 7}$$

After the quantification of bypassed oil, the next step was to predict the production and economics of the undiscovered reservoir. As part of this effort, a correlational model has been developed for the prediction of reserves and production for the target resource. The steps involved in characterizing the production profile of each undiscovered reservoir were as follows:

1. Calculate recovery efficiency for the bypassed oil block.
2. Calculate the cumulative production associated with the recovery efficiency, as per step 1.
3. For each year, calculate the fractional recovery as a function of the cumulative oil production and reservoir properties.
4. Calculate annual production in each year.
5. Repeat steps 3-4 for oil, gas and water production.

These steps are described in more detail below.

3. Development of Recovery Efficiency Correlation Using Boast3-PC

a. Reservoir Model Grid and Geometry

For the purpose of setting up the model, a 15 by 11 by 1 grid was used, comprising of a total area of about 80 acres. Each gridblock in the grid was assumed to have the same size and dimension. The elevation value to the top of the grid was an input to the model. Using the angle of inclination of the reservoir (Alpha) greater than zero for downward dip in the x direction, elevation values of the different grid blocks were computed by the simulator. Figure IV-8 illustrates the grid used for simulation.

b. Rock Properties

Porosity, permeability and initial oil saturation are the major rock properties required for the simulation. An average porosity of 30% was used for the entire field. As no permeability data were available, a correlation between the permeability and porosity was developed using the data in the simulation study of South Marsh Island 73 Field (Reference 1). The correlation between the permeability and porosity as shown in Figure IV-9 was considered representative for the reservoirs in the Gulf of Mexico. Each reservoir was assumed to have an initial oil saturation of 83.5%.

Figure 4-8
Grid Layout of Bypassed Oil Model

NOTE: FIGURES NOT DRAWN TO SCALE

Figure IV-9
Correlation between Permeability and Porosity
 $\text{Log}_{10}(\text{Perm}) = -1.3999 + 14.2485 * (\text{Por})$

Note: Data taken from South Marsh Island Block 73 Field Reservoir Simulation Study B-35 Sand, Reservoir K

c. Relative Permeability Curves

BOAST3-PC requires relative permeability curves as part of the input data set to simulate the three phase flow of oil, gas, and water in a reservoir. For the purpose of the model, the empirical data used for the simulation study reference above was used.

d. PVT Data

PVT data is representative of the fluid properties of the reservoir fluids and its interaction with various reservoir properties. Deriving a set of PVT data using the reservoir conditions required the use of several empirical correlations (Reference 2). These correlations were used to determine values for bubble point pressure, solution gas-oil ratio, formation volume factor, and viscosity.

e. Water Influx

All reservoirs in the Gulf of Mexico are subjected to some kind of natural water drive. A steady state aquifer model option was used for simulating water drive. Based on the calculations illustrated in the simulation study of South Marsh Field (Reference 1), a model constant of 7.58 scf/day/psi was used to grid block in contact with the aquifer. This value is representative of a strong water drive.

Each well was allowed to produce at a bottom hole pressure of 50 psi. The rate of production was calculated by the simulator. The well was allowed to produce oil, gas and water to the maximum water-oil ratio of 99, after which the well is no longer in production.

The following constant values of the key parameters were used to develop the recovery correlation for estimating bypassed oil recovery potential:

1. API Gravity	= 30 degrees
2. Porosity	= 30%
3. Permeability	= 144 md.
4. Water Cut	= 99.00%
5. Dip Angle	= 4 degrees
6. X - location	= 0.50
7. Y - location	= 0.50
8. Initial Oil Saturation	= 83.5 %

The above parameters were then varied individually over a wide range while keeping others constant. The results of the simulation results are tabulated in Table IV-5. These results were then normalized to ultimate recovery using a multivariate regression analysis. It was observed that the logarithmic equation of the form:

$$Y = C_0 X_1^{C_1} X_2^{C_2} X_3^{C_3} \dots X_n^{C_n}$$

was the best expression to represent recovery as a function of the above mentioned key parameters. The results of the regression analysis are shown in Figure IV-10.

Table IV-5
BOAST Results for Bypassed Oil Recovery

Property	Value	CUM OIL	OOIP	Rec. Frac.
		MSTB	MSTB	of OOIP
API (degree)	20	4403	8586	0.5128
	25	4608	8471	0.5440
	30	4156	7770	0.5349
	35	4171	7648	0.5454
DIP (degree)	1	4113	7631	0.5390
	4	4171	7648	0.5454
	6	4293	7714	0.5565
	9	4430	7679	0.5769
	12	4454	7696	0.5787
	15	4466	7712	0.5791
	18	4494	7725	0.5817
	22	4515	7751	0.5825
	25	4549	7788	0.5841
	30	4548	7791	0.5838
POR (fraction)	0.10	1447	2549	0.5677
	0.15	1986	3824	0.5194
	0.20	2736	5098	0.5367
	0.25	3616	6373	0.5674
	0.30	4171	7648	0.5454
	0.35	4972	8922	0.5573
PERM (mdarcy)	10	3550	7648	0.4642
	100	3934	7648	0.5144
	144	4171	7648	0.5454
	500	4317	7648	0.5645
	1000	4460	7648	0.5832
	1500	4538	7648	0.5934
	2000	4589	7648	0.6000

Property	Value	CUM OIL	OOIP	Rec. Frac.
		MSTB	MSTB	of OOIP
SOI (fraction)	0.700	3287	6411	0.5127
	0.750	3701	6869	0.5388
	0.800	4116	7327	0.5618
	0.835	4171	7648	0.5454
	0.850	4172	7785	0.5359
XLOC (fraction)	0.10	1573	7648	0.2057
	0.23	3189	7648	0.4170
	0.30	3352	7648	0.4383
	0.50	4171	7648	0.5454
	0.70	4594	7648	0.6007
	0.90	4644	7648	0.6072
YLOC (fraction)	0.14	4547	7648	0.5945
	0.32	4535	7648	0.5930
	0.50	4171	7648	0.5454
	0.77	4666	7648	0.6101
	0.95	4638	7648	0.6064
WCUT (fraction)	0.10	3275	7648	0.4282
	0.20	3295	7648	0.4308
	0.30	3307	7648	0.4324
	0.40	3316	7648	0.4336
	0.50	3336	7648	0.4362
	0.60	3342	7648	0.4370
	0.70	3363	7648	0.4397
	0.80	3446	7648	0.4506
	0.90	3468	7648	0.4535
	0.95	3472	7648	0.4540
	0.96	4121	7648	0.5388
	0.99	4171	7648	0.5454

Figure IV-10
BOAST Simulated vs. Log Model Results

4. Economics of Bypassed Oil

a. Introduction

In 1984, the National Petroleum Council (NPC) developed cost estimation relationships for use in an analysis of the potential of enhanced oil recovery (EOR) in the United States. These equations and relationships were used in the costing routines of the Department of Energy's (DOE's) Tertiary Oil Recovery Information System (TORIS), which are maintained, updated, and applied by the DOE's Bartlesville Project Office (BPO). The cost relationships and equations used in the TORIS models and data bases were last updated in 1994. Similar cost relationships were developed for recovery of bypassed oil to maintain consistency in the economic calculations.

Both process independent and incremental process dependent costs were examined for primary production of bypassed oil. The raw data for the process independent costs were obtained from available data sources, including the Joint Association Survey on Drilling Costs (1993) and Energy Information Administration (EIA). Process independent costs estimate the expenses associated with installing and operating primary production for flowing wells. There were no incremental process dependent costs associated to the producing wells. In order to be consistent with TORIS, the raw cost data was converted to constant 1993 dollars when necessary. The regression analyses were then performed on the revised data.

The following process independent costs were considered in the economic evaluation of bypassed oil recovery potential:

- Drilling and completion costs
- Operating costs for flowing well
- Cost to equip a new producer

The following sections explain the cost updates in more detail and present new cost equations for the bypassed oil economic model.

b. Drilling and Completion Costs

Drilling costs, as contained in TORIS models, incorporate the cost to drill and complete an oil well (including tubing costs) and logging costs. Drilling and completion (D&C) costs, like the operating and equipment costs discussed in the following sections, have been modeled as a function of depth. For this analysis, the actual D&C costs were obtained from the *1993 Joint Association Survey on Drilling Costs*. The JAS contained state level data of which the Gulf of Mexico offshore data was used for this study. The D&C cost data was normalized to a \$30/Bbl oil price using the appropriate energy factor. Regression analyses were conducted on the normalized D&C costs. Several different cost/depth relationships were examined:

$$\text{D\&C Costs (\$/Well)} = b_0 + (b_1 * \text{Depth}) + (b_2 * \text{Depth}^2) + (b_3 * \text{Depth}^3) \quad (1)$$

$$= b_0 + (b_1 * \text{Depth}) + (b_2 * \text{Depth}^2) \quad (2)$$

$$= b_0 + (b_1 * \text{Depth}) + (b_3 * \text{Depth}^3) \quad (3)$$

$$= b_0 + (b_2 * \text{Depth}^2) + (b_3 * \text{Depth}^3) \quad (4)$$

$$= b_0 + (b_1 * \text{Depth}) \quad (5)$$

$$= b_0 + (b_2 * \text{Depth}^2) \quad (6)$$

$$= b_0 + (b_3 * \text{Depth}^3) \quad (7)$$

Each of the evaluated equations assumes a fixed set-up cost, rather than a pro-rated cost. After analyzing the least-squares curve fit and the fixed set-up costs, equation (1) was selected as the D&C cost calculation equation. The equation for the drilling cost is as follows:

$$\text{D\&C Costs (\$/Well)} = b_0 + (b_1 * \text{Depth}) + (b_2 * \text{Depth}^2) + (b_3 * \text{Depth}^3)$$

where

$$\begin{aligned} b_0 &= 1031.8557 \\ b_1 &= -0.0372088 \\ b_2 &= 0.00 \\ b_3 &= 2.0733\text{e-}9 \end{aligned}$$

Figure IV-11 exhibits the drilling and completion cost as a function of depth for the offshore fields.

Figure IV-11
Drilling Cost (@\$30) vs Depth

Note: Actual Data taken from Join Association Survey on 1993 Drilling Costs

c. Operating and Maintenance Costs

In offshore fields, fixed operating costs are relatively high, corresponding to the costs for maintaining the platform, wages of personnel on board, transportation of material and personnel and other associated costs. A fixed operating cost of \$200,000/well/year was used for the purpose of this study.

Since empty slots in the existing platform will be used for operating new wells, no new production equipment costs was added.

The results of the economic model were used to summarize the Federal royalties, contribution to GDP, Federal taxes and most important to predict the economical bypassed oil reserves in the Gulf of Mexico. These results were evaluated on reservoir by reservoir basis and are presented in chapter 3.

5. Decision Analysis

a. Overview

The analytical model developed in this section can only predict the gross volume of bypassed oil. Up to this point, the model does not predict where the bypassed oil is located or how it is distributed if more than one fault block is present. However, such information is required in order to decide where to drill and how many new wells are required. In this study, because of the lack of empirical and field data, a probabilistic approach has been developed in order to approximate the likely location of the bypassed oil volume. The approach is based on *decision analysis* as discussed in the following section.

b. Rationale

Decision analysis is widely applied in petroleum exploration where the associated costs are very high. Without the aid of decision analyses, the expected value of any project would be very optimistic and misleading. In the current problem, decision analysis is used in placing the unknown fault blocks. The expected value of drilling a particular site is dependent on the expected value and probabilities of the other decision elements in the tree.

Many different forms of decision trees can be adapted to suit the nature of this problem. One such tree was evaluated and validated to suit the requirements of the project. This tree may not represent a true picture for all of the reservoirs, but could be used as a guideline to evaluate the undiscovered potential. Once advanced technology factors affecting the mapping of the reservoirs has been resolved, the decision tree can be expanded and updated to evaluate a more representative potential.

c. Structure of Decision Tree

Decision analysis is implemented through the use of a decision tree. The structure of a decision tree consists of two main forks. The first is a decision fork, noted by square nodes with decision branches. Decision nodes are events in the tree where a decision must be made. The value of the decision node is equal to the best case scenario of all the possible decisions, i.e. the branch with the best expected value. Decisions in our tree are whether to drill for oil or not. The decision to drill will only be made if the expected value of drilling outweighs the expected value of not drilling.

The other kind of fork is a probability fork, noted by a circle with the appropriate probabilities branching out. Each branch has a probability assigned to it. Probability nodes are inserted where events are uncontrollable. Probabilities in our tree are whether a well will produce oil or not. The value of a probability node is equal to the expected value of all the branches. If a well has a 20% chance of striking oil and making \$100,000, and an 80% chance of missing oil and losing \$20,000, then the probability node of this event is equal to $(0.20)(\$100,000) + (0.80)(-\$20,000) = \$4,000$.

d. Construction of Decision Tree

There are four steps involved in creating a decision tree:

- Layout of all possible cases
- Assigning probabilities to each case
- Drawing the tree
- Calculating the value of the tree.

Each of the above-mentioned steps are discussed below in detail:

i. Layout of Possible Cases

Estimating the different possible cases for each reservoir relies heavily on the theory of self-similarity in nature. This theory suggests that, under uniform pressure and land formations, faults form around a salt dome homogeneously, i.e. the faults will be equally spaced within each reservoir. For example, if a reservoir is 21° wide and contains 1 existing well, and it can be calculated that this well has drained oil from a pocket 7° thick, it can be assumed that there are 2 additional pockets that are also 7° thick (see Figure IV-12). Call this Example 1.

Figure IV-12

Example 1

This example worked out nicely because of the numbers that were chosen. But in real world conditions, numbers usually do not divide out evenly. Therefore, different solutions must be found with different probabilities assigned to each outcome. For example, suppose a reservoir is 20° wide and has a well draining from an 8° pocket. Call this Example 2. Now there are options as to what the mapping may look like. By following the self-similarity theory, there can be 1 new pocket of 12° or there can be 2 new pockets of 6° each. (Although there are other cases to consider, we chose to focus on these two.)

The above analysis estimates the *area* associated with each fault zone. It does not take into account the *location* of the fault zone. The location of the new fault blocks are dependent on the location of the existing wells. For instance, suppose in Example 2 that the well is located at the 7° mark of the reservoir. Now there are three possible cases using our method (Figure IV-13).

Figure IV-13

Illustration of Possible New Fault Pockets for Example 2

These three cases can be grouped into two categories: a minimum pocket scenario (Case 1) and a maximum pocket scenario (Cases 2 and 3). It turns out that this is as complicated as it gets. All the reservoirs in our study will have at most three cases. In fact, all one-well reservoirs will have at most one minimum pocket scenario, and either 1 or 2 maximum pocket scenarios. This fact stems directly from the homogeneous faults theory and can be proven mathematically. If this theory is not valid, then this generality cannot be made.

It is interesting to note that the area between 14-20° is undrained in all three cases in Example 2 (see Figure IV-13). This “overlapping” phenomenon can also be generalized to all the reservoirs in the study and it plays an important part in developing the decision tree.

ii. Probabilities

Probabilities must be assigned to all cases as a sort of confidence factor. Since we do not have enough information to distinguish between the cases, we weighted each case equally.

iii. Drawing the Tree

To explain the structure of the tree, it is easier to first present a specific case, and then generalize it to cover all reservoirs. The tree for Example 2 (Figure IV-13) is shown in Figure IV-14. Again, all the decisions in the tree are whether to drill in certain locations or not, and all the probabilities refer to the chance of hitting oil in these spots.

Note that the first decision is whether or not to drill in the 14-20° range. This range was chosen as the first drilling site because it is common in all three cases. This will be a guaranteed drill (that is why there is no probability node after it). If the decision is made not to drill here, the tree ends. This makes sense, though, since the 14-20° range is the best place to drill in the reservoir. So why would you want to drill elsewhere if you just passed up the most optimal site? The tree branches out after the first decision node, with each path representing each of the possible permutations for drilling the reservoir.

Figure IV-15 demonstrates the generalized version of the decision tree. Because of the nature of the assumptions, certain generalizations can be made from Example 2. In particular, there will always be a 'guaranteed' drilling site, and at most three cases. Therefore, the shape of the tree is exactly the same as in Figure IV-14. Note that in certain reservoirs only one mapping is physically possible. For these instances, the probabilities are just adjusted so that one of the cases has a 100% chance of being correct, and the other two are 0%. The decision tree will still be valid, but with updated probabilities.

iv. Expected Potential Evaluation

Calculating the potential for each reservoir is done in two steps:

1. Find the optimal path in the tree by maximizing the net present value (NPV) of the profit. This is done by calculating the profit NPV for each end node, and then working backwards to the initial node.
2. Once the optimal path is found, reserves, among other values, can be easily calculated by just following the same path that maximized the profit NPV. For example, if maximizing

Figure IV-14
Decision Tree for Estimating the Potential of the Reservoir in Example 2

Figure IV-15
General Decision Tree for Estimating the Potential of One-Well Reservoirs

profit meant drilling two wells then stopping, then reserves can be forecasted (as discussed in Section IV.C.2) for drilling two wells.

The above methodology is coded in a FORTRAN program. The program evaluates the expected potential and economics of each reservoir based on the optimal path of maximizing profit. Results of the analysis were then used to evaluate the bypassed oil reserves in the Gulf of Mexico.

D. METHODOLOGY FOR ATTIC OIL RECOVERY

1. Introduction

Attic oil recovery by updip gas injection is widely used in the Gulf of Mexico. It is a single well injection and production process. The process of injection and production is widely discussed in Chapter 2. It is evident from the literature survey, and from previous computer simulations and laboratory experiments conducted by various personnel that the most significant operating parameters for this process are gas injection rate, gas injection volume, and shut-in period for gas migration. The most significant reservoir parameters which effect the recovery of attic oil are permeability, porosity and dip angle.

The objective of this study is to develop a predictive model to estimate recovery of attic oil by an updip gas injection process. For this purpose, BOAST3-PC was modified by LSU. The predictive model developed was based on runs conducted using BOAST3-PC and correlations developed as a function of the key parameters discussed above.

Input data for the BOAST3-PC run was set up in the same manner as that for the bypassed oil. This was done in order to maintain consistency in the reservoir and fluid properties which were considered to be representative of the Gulf of Mexico offshore reservoirs. Historically, the field where updip gas injection process is used, the wells are perforated in the upper half of the sand. If single layer model is assumed, BOAST3-PC assumes perforation in the complete sand. Thus, a grid of 15x7x3 was used for simulating performance of updip gas injection which had a total area of about 40 acres. Figure IV-16 exhibits the gridblock layout and the position of the well.

Each layer in the model was considered to be homogeneous and of constant thickness. Porosity of 30% and horizontal permeability of 250 md was used as an average and representative of the Salt

Piercement reservoirs. Vertical permeability of 10% of the horizontal permeability on each layer was introduced to simulate communication between the layers.

The input data file for BOAST3-PC model was created to simulate primary production from strong water drive to initialize reservoir conditions for the gas injection/production process.

- **Injection of gas.** The upmost wells which had a location of 60% or higher were used for injection of gas. A constant bottomhole pressure of 3000 psi was maintained. This pressure was considered to be a pressure higher than the current reservoir pressure. The well was allowed to inject at a maximum injection rate of 7000Mcf/day. Actual rate of injection was calculated by the model at various time steps. A total injection period of about 80 days was considered to be optimum for the size of reservoir.
- **Shut-in Period.** This is the period when the gas migrates updip and due to density difference of the oil and gas combined with the effect of gravity segregation oil moves down from the attic and thereby pushes the water-oil contact down. The period of shut-in after gas injection is very important. It does not have any correlation with the dip angle of the reservoir. Though there is a optimum shut-in period for each dip angle which has to be determined separately, and then used as one of key parameters for recovery evaluation. Initially, a period of 480 days was chosen as an optimum shut-in period. Several runs were conducted to achieve an optimum shut-in period as a function of dip angle. The results are in Table IV-6.

Table IV-6
Optimum Shut-in Time as a Function of Dip Angles

Dip Angle (degrees)	Optimum Shut-In Time (days)
6	700
9	700
12	300
15	480
18	300
25	480
22	300
30	480

Figure 4-16
Grid Layout for the Attic Oil Recovery Model

- **Production of attic oil.** After the shut-in period the well is allowed to produce for the period of time until it either produces a high water oil ratio (WOR) or gas oil ratio (GOR). The well shuts in according to the constraints setup in the input data file. WOR of 90 and GOR 3,000,000 was considered to be constraints for shut-in of well during production.

Two cycles of injection/production were used for the model. Several BOAST runs were done in order to come up with a profile of recovery as function of varying key parameters. The recovery of attic oil in each cycle can be stated as

$$f = (\text{dip angle, porosity, permeability, } x - \text{location, shut-in period})$$

The results of various runs at varying key parameters are tabulated in Table IV-7.

Once these tables were developed, a multivariate linear regression analysis was used to predict the recovery in each cycle as a function of the parameters mentioned above. The recovery of oil in various cycles is of the form

$$\text{Recovery} = a + b X_1 + c X_2 \dots\dots\dots$$

where, $X_1, X_2, X_3,$ are values of the key parameters
(dip angle, porosity, permeability, y location, shut-in time).

Coefficients of regression equation of various cycles are tabulated in Table IV-8. These equations were further coded in FORTRAN model to predict the performance.

2. Economics of Attic Oil Production

The economic model for attic oil recovery is a modified version of the bypassed oil economic model. Details of the model are already discussed in an earlier section.

The changes incorporated in this model are related to various process independent and dependent costs. The process independent costs considered are as follows:

1. No drilling cost
2. Fixed platform operating cost of \$200,000/year

Table IV-7
BOAST Results for Attic Oil Recovery

Item	Value	Initial	Attic - Cycle 1		Attic - Cycle 2		Total	
		OOIP	Production	Recovery	Production	Recovery	Production	Recovery
		MSTB	MSTB	Frac OOIP	MSTB	Frac OOIP	MSTB	Frac OOIP
DIP (degree)	0	2496	68	0.0272	25	0.0100	1213	0.4860
	4	2472	46	0.0186	75	0.0303	1223	0.4947
	6	2495	86	0.0345	133	0.0533	1338	0.5363
	9	2497	76	0.0304	139	0.0557	1347	0.5394
	12	2500	122	0.0488	79	0.0316	1340	0.5359
	15	2504	94	0.0375	162	0.0647	1406	0.5615
	18	2507	141	0.0563	108	0.0431	1409	0.5621
	22	2517	127	0.0505	147	0.0584	1449	0.5756
	25	2514	138	0.0549	113	0.0450	1431	0.5693
	30	2519	0	0.0000	280	0.1112	1475	0.5856
POR (fraction)	25	2098	128	0.0610	150	0.0715	1264	0.6026
	30	2517	127	0.0505	147	0.0584	1449	0.5756
	35	2937	126	0.0429	140	0.0477	1625	0.5533
PERM (mdarcy)	100	2517	252	0.1001	95	0.0377	1376	0.5466
	250	2517	127	0.0505	147	0.0584	1449	0.5756
	500	2517	134	0.0532	152	0.0604	1458	0.5792
	800	2517	105	0.0417	171	0.0679	1443	0.5732
YLOC (fraction)	50	2517	127	0.0505	147	0.0584	1449	0.5756
	70	2517	227	0.0902	69	0.0274	1544	0.6134
	76	2517	248	0.0985	41	0.0163	1483	0.5891
	83	2517	293	0.1164	29	0.0115	1468	0.5832
SOAK (days)	50	2517	91	0.0362	159	0.0632	1425	0.5661
	240	2517	127	0.0505	161	0.0640	1463	0.5812
	300	2517	126	0.0501	171	0.0679	1472	0.5848
	480	2517	127	0.0505	147	0.0584	1449	0.5756

Table IV-8
Constants and Coefficients for Various Regression Equations

		Dip coeff	Por coeff	Perm coeff	YLoc coeff	Shut-In coeff
Estimates:	Constant	a1	a2	a3	a4	a5
Rec for Cycle 1	-0.01566	0.00086	-0.00181	-0.00003	0.00196	0.00002
Rec for Cycle 2	0.17435	0.00170	-0.00238	0.00002	-0.00158	-0.00001
% of Cycle 1 Rec in Yr 1	0.51430	-0.00512	-0.00744	0.00041	0.00576	0.00043
% of Cycle 2 Rec in Yr 1	0.04105	-0.00664	0.01724	0.00037	0.00545	0.00015

The process dependent costs considered are :

1. Gas injection cost: Gas price based on oil price (\$/Mcf)
2. Compression cost of \$0.45/Mcf
3. No equipment cost.

The above costs are based on industry survey and data published in the literature. Economic results were evaluated on a reservoir-by-reservoir basis and cumulative results of the analysis are provided in Chapter III.

References

1. BDM Federal, Incorporated, 'South Marsh island Block 73 Field reservoir simulation Study, B-35 Sand, Reservoir K', October 1993.
2. R.P.Sutton, *Evaluation of Empirically Derived PVT properties for Gulf of Mexico Crude Oils*, SPE# 13172.

V. RECOMMENDATIONS FOR FUTURE EFFORTS

The analytical models and the database developed as part of the present effort has major limitations and constraints as discussed below:

- **Data Collection and Processing.** The data collection effort concluded that there are several major problem areas which prohibited collection of all required data for 1,289 salt dome fields/reservoirs as initially intended. These areas include: (1) unavailability of geologic maps for a large number of fields, (2) inadequate maps, unreadable maps or maps without scales or labels, (3) inconsistencies in well name and reservoir name between the maps and the MMS electronic databases, and (4) out-of-date maps not showing location of wells drilled after 1980. It is recommended that efforts be expended to update the map information and also to resolve the discrepancies between the different sources of data from the MMS files. Only through such efforts can DOE benefit from a representative database of the salt dome reservoirs for its planning and analysis activities.
- **Characterization of Bypassed Oil Due to Inaccurate Detection of Salt Boundary.** A large quantity of oil has been bypassed because of the salt boundaries not clearly visible in seismic data. This resource could not be evaluated due to the lack of case histories or empirical data to justify its modeling. The MMS, however, could be instrumental in gaining access to the new or reinterpreted seismic data from the operators in the Gulf of Mexico. A joint DOE and MMS effort could provide enough case histories to build an empirical or statistical model for the characterization of this very important resource.
- **Characterization of Bypassed Oil Due to Faulting.** The following are recommended areas for future improvements to the bypassed oil predictive model:
 1. Fault Block Size. The prediction of the fault block size is the most important aspect of evaluating the resource and the economics of bypassed oil due to faulting. In this effort, based on the self similarity theory, the size of the bypassed oil blocks was assumed to be equal to the size of the drained blocks. This assumption was made in absence of fault block size distribution data for salt dome reservoirs. Efforts should be expended to collect and analyze published data for fault block size distribution in order to build an empirical model for the prediction of the size of the undrained fault blocks.
 2. Constant Water Influx. All reservoirs in the Gulf offshore are subjected to water influx of varying degree. Efforts should be expended in order to collect relevant reservoir and pressure data to predict water influx rate. In this analysis, due to lack of data, a constant water influx rate was used to simulate production.
 3. Permeability. The FRRE database does not have any permeability data. In this analysis, a porosity/permeability correlation was used to estimate the permeability values by default for all the fields in the analysis. This data should be collected from operators based on the core/laboratory results.
 4. Technology Criteria. Present analysis of bypassed oil evaluates the resource based on current technology. Due to the assumption made regarding the size of the fault blocks, the decision tree analysis leads to only one decision without taking benefit of the advanced

technology scenario. The advanced technology scenario can only be evaluated once a reasonable methodology is developed for predicting the size of undrained fault blocks.

- **Attic Oil Recovery.** In the present analysis, a correlational predictive model was developed based on simulation results using DOE's BOAST3-PC. It was observed, however, that BOAST3-PC predicted unreasonably large volumes of gas when the reservoir pressure falls below bubble point pressure. This behavior of the simulator can, without doubt, affect the result of the gas injection process. It is recommended that such problems in the simulator be fixed and the model be tested and validated against field results or other simulators. The process of gas injection has been proven and publications are available discussing the theory and the field results. This information should be used to develop a comprehensive predictive model for updip gas injection. Such a model should allow incorporation of the elements of technology improvements in order to measure the benefits of R&D in updip gas injection for DOE.

Although the present analysis focuses on the characterization of unrecoverable mobile oil, there are large volumes of immobile reserves associated with the salt dome reservoirs in the Gulf of Mexico. DOE should consider evaluating the recovery of this immobile oil resource using enhanced oil recovery techniques. At present, the DOE's predictive models do not handle dipping reservoirs. However, modifications could be made to the predictive models in order to handle dipping reservoirs. Once these modifications are done, DOE could then have complete capabilities to evaluate the entire resource of salt dome reservoirs in Federal offshore Gulf of Mexico.