Assistant Secretary for Energy Technology
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Enhanced Recovery of Unconventional Gas

MASTER

Executive Summary— Volume 1 (of 3 Volumes)

MASTER

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Enhanced Recovery of Unconventional Gas

Executive Summary— Volume 1 (of 3 Volumes)

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REVIEW DRAFT NOTE

This report consists of three volumes:

Volume I: Executive Summary

Volume II: The Program

Volume III: Methodology

Because of demand for the results of this study, review drafts of the first two volumes are being published before Volume III is complete. A draft of Volume III will be issued shortly, at which time it will receive the same distribution as Volumes I and II.

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THE PUBLIC POLICY ISSUES

I. INTRODUCTION

As the conventional domestic natural gas supplies dwindle, the nation increasingly must look for ways to slow these trends and seek new supplies. The choices faced are controversial, costly, and risky. They entail difficult balancing among higher prices, accelerated development, reliance on imports, and new technology.

Part I of the Executive Summary* of the study of enhanced gas recovery serves to assist public decision makers select among the many choices by addressing three strategic questions:

- How severe is the need for additional future supplies of natural gas?
- What is the economic potential of providing a portion of future supply through enhanced recovery from unconventional gas resources?
- Is it more cost-beneficial to use price,** public R&D, or a combination of both to stimulate the potential of the unconventional gas sources?

* Part II of the Executive Summary and the full report, *Enhanced Recovery of Unconventional Gas*, provide further analysis of these three questions and a framework for designing a cost-effective DOE research and development program to stimulate industry to recover this unconventional source gas and to produce it sooner. Part III of the Executive Summary provides a review of the methodology and acknowledges the many individuals that contributed to this study.

** The term "price", used in the paper, serves to summarize any combination of economic incentives such as market price, tax provisions, public subsidies, etc., that can be expressed in "price to the public" equivalent terms.

II. BACKGROUND

Until recently, the more conventional sources provided enough natural gas to meet the nation's demand. It was neither necessary nor economic to develop anything more than the discovered conventional reservoirs or the "cream" of the unconventional resources.*

Now, with sharply declining production from these conventional sources, it is essential to re-examine this posture.

Analyses of natural gas supply indicate that the natural gas curtailments of the winter of 1976/1977 were not abnormalities but are predictable and, unless counteracted, recurring phenomena. Without new programs or substitute gas sources, the prospects for future shortfalls in natural gas supply are grave.

This study recommends that research and development efforts in enhanced gas recovery of near-conventional and unconventional gas sources should be one among a number of programs pursued for augmenting domestic supplies. Within the R&D program, three goals need to be vigorously pursued if the unconventional gas sources are to make a significant near-term impact:

-
- * The better portions of the "unconventional sources" of gas have been under active exploitation or study for many years:
- Almost 3 Tcf of gas has been produced from the *Devonian shales* since the turn of the century, with another 1 Tcf in proved reserves yet to be produced.
 - Drilling in the more favorable portions of the low permeability *tight gas basins* has been underway for over 30 years and has yielded over 10 Tcf.
 - *Methane emissions from coal seams* -- an historic hazard to coal mining -- have averaged about 0.1 Tcf per year, although none is currently captured for commercial markets.
 - Finally, even the *geopressured aquifers*, the least defined of the unconventional natural gas sources, have been placed under testing during the past year.

Exhibit 1
The Potential of Gas from Unconventional Sources

* IN CONSTANT 1977 DOLLARS.

The remainder of Part I of the Executive Summary consists of: (1) a perspective on domestic natural gas supplies; (2) summary findings on the economics and potential of augmenting domestic gas supplies from unconventional sources; and (3) the public policy options that would most cost-effectively stimulate the recovery of these additional gas supplies.

III. DOMESTIC GAS SUPPLY

A. The Role of Conventional Sources

Natural gas, the nation's second most utilized fuel, provides about thirty percent of the country's total energy requirements. As the use of natural gas grew during the early 1970's, the domestic capacity to sustain this use declined. The effects of this were felt first through periodic curtailments and finally during the winter of 1976/1977 by severe industrial disruption.

Continuing shortfalls are predictable without a change in the current situation:

- New discoveries and extensions of known fields have replaced less than one-half of the gas consumed over the last seven years.
- Total proved reserves as a result have declined by 26% since 1970, from 290 Tcf to 216 Tcf. Of the 216 Tcf, 32 Tcf are in Alaska, unavailable without a pipeline or other means of transportation -- leaving only 184 Tcf in readily accessible proved reserves.
- With annual production running at 19.5 Tcf, the ratio of proved reserves to production is at an all time low, about 11 to 1; at current production rates and without new additions, the nation has an eleven year gas supply in terms of recoverable reserves -- about nine and a half years when Alaska is excluded.

Production from *conventional sources** of domestic natural gas under a gas price of \$1.75/Mcf and current technology shows a continuing downturn throughout the rest of this century (Exhibit 2).

SUPPLY OF CONVENTIONAL SOURCE NATURAL GAS

<u>Year</u>	<u>Tcf/Year</u>
1978	19
1980	17
1985	13
1990	11
2000	8

Without improved economics or major new frontiers,** domestic supplies from *conventional sources* will fall far short of historic levels of gas use.

B. The Current Contribution of Unconventional Sources

The unconventional natural gas resources, particularly the more geologically favorable tight gas basins, even now significantly contribute to domestic production. These sources currently provide about 1 Tcf per year and could provide, under Base Case*** (current and near term technology) assumptions, over 2 Tcf in 1990.

* Including currently proved reserves, excluding Alaska, inferred reserves added to known fields, and the seven-year historic rate of new discoveries.

** A full analysis of price/supply elasticity of conventional gas sources was beyond the scope of this study; thus, all projections of conventional gas supply were made at \$1.75 per Mcf. However, the geologic data and the analysis of near-conventional gas sources show that important additions to supply could accrue only after prices reach threshold levels that open up major new, and heretofore uneconomic, frontiers.

*** The Base Case assumes industry as a whole would apply the technology that is currently the state of the art.

Exhibit 2

**Projected Production from Conventional Gas Reserves
(at Gas Prices of \$1.75/Mcf)**

1/ RESERVES OF CRUDE OIL, NATURAL GAS LIQUIDS AND NATURAL GAS IN THE UNITED STATES AND CANADA AS OF DECEMBER 31, 1976, BY AGA/API/CPA.

2/ BASED ON A RECENT LEWIN AND ASSOCIATES, INC., STUDY, ANALYSIS OF THE TIMING AND TOTAL OF INFERRED RESERVES OF NATURAL GAS IN THE CONTIGUOUS UNITED STATES, BY J. BRASHEAR AND F. MORRA.

3/ BASED ON ONSHORE (LOWER 48) DISCOVERIES OF 1.0 TCF/YEAR AND OFFSHORE (LOWER 48) DISCOVERIES OF 0.5 TCF/YEAR, GROWING TO 3.9 AND 1.9 TCF RESPECTIVELY THROUGH DEVELOPMENTAL DRILLING.

With this, total gas supply from domestic sources without advances in technology would be as follows:

DOMESTIC GAS SUPPLY FROM ALL SOURCES WITHOUT ADVANCES IN TECHNOLOGY (AT \$1.75 PER MCF)			
Year	Conventional* Sources	Additional Base Case Unconventional Sources (at \$1.75/Mcf)	Total Anticipated Domestic Supply
1980	17	**	17
1985	13	1	14
1990	11	2	13
2000	8	3	11

Even with these additions from unconventional sources, by 1985 domestic natural gas supply will be 6 to 8 Tcf below recent usage and as much as 10 Tcf short by 1990. Exhibit 3 provides a display of total anticipated domestic supply of natural gas between now and the year 2000 under current economic and technological conditions. It is clear that still other options will need to be considered to avoid a serious natural gas shortfall.

C. Major Trade-Offs for Increasing Domestic Gas Supply

Several choices are available to public policy-makers seeking to increase natural gas supply and thus close this gap, including:

- Improving the economic incentives for gas production, through higher prices or more favorable taxes.

* The supply from conventional sources already includes some unconventional gas production, calculated at about 1 Tcf in 1977. The gas from unconventional sources estimated by this study is in addition to the amounts already proved and being produced from unconventional sources.

** Less than 0.5 Tcf per year.

Exhibit 3
**Total Domestic Gas Supply — Conventional and Unconventional
 Sources (at Gas Prices of \$1.75/Mcf and Current Technology)**

- 1/ BASED ON AGA/API/CPA, RESERVES OF CRUDE OIL, NATURAL GAS LIQUIDS AND NATURAL GAS IN THE UNITED STATES AND CANADA, DECEMBER 31, 1970 THROUGH 1976.
- 2/ BASED ON THE LEWIN AND ASSOCIATES, INC. STUDY, ANALYSIS OF THE TIMING AND TOTAL OF INFERRED RESERVES OF NATURAL GAS IN THE CONTIGUOUS UNITED STATES, BY J. BREASHEAR AND F. MORRA, REPORTED IN VOLUME III OF THIS REPORT.
- 3/ BASED ON ONSHORE (LOWER 48) DISCOVERIES OF 1.0 TCF/YEAR AND OFFSHORE (LOWER 48) DISCOVERIES OF 0.5 TCF/YEAR, GROWING TO 3.9 AND 1.9 RESPECTIVELY THROUGH DEVELOPMENTAL DRILLING.
- 4/ FROM THE 1978 STUDY OF ENHANCED GAS RECOVERY FROM UNCONVENTIONAL SOURCES BY LEWIN AND ASSOCIATES, INC.

- Stimulating frontier exploration, through accelerated and innovative leasing policies.
- Negotiating secure, imported sources for natural gas and LNG.
- Accelerating the development of coal, heavy oil, or shale gasification.
- Developing improved technology (enhanced gas recovery) for further developing the unconventional sources of gas.

A mix of the above economic and technological choices appears required to avert serious shortfalls. This summary argues that focused research and development of enhanced gas recovery can substantially increase gas supply from unconventional sources and provide an economic and highly cost-effective near- and long-term option.

The next section provides price, supply, and cost data on unconventional gas sources to assist policy makers in making a prudent choice.

IV. GAS FROM UNCONVENTIONAL SOURCES -- A SUMMARY OF ITS ECONOMIC POTENTIAL

The study of enhanced gas recovery finds that: (1) unconventional sources of natural gas already provide about 1 Tcf per year to domestic gas production;* (2) the gas production industry has and will continue to make significant technological advances in certain of the more defined unconventional gas areas and, depending on gas price, would provide from 2 to 3.5 Tcf of gas per year by 1990, as described in the Base Case; and (3) significant additions to recovery and acceleration of production could accrue from a successful Federal-industry collaborative R&D program in enhanced gas recovery, raising the total contribution of the unconventional gas sources to a range of 6 to 8 Tcf per year by 1990 (depending on price), as described below as the Advanced Case.

A. Base Case**

Even under Base Case technology and a gas price of \$1.75 per Mcf, the unconventional sources can provide an important addition to domestic gas supply -- about 2 Tcf per year by 1990.

Increasing price (or its economic equivalent) to a range competitive with other energy sources,*** from \$1.75 per Mcf to \$3.00 per Mcf, increases ultimate recovery from unconventional gas resources from about 70 Tcf to over

* The primary source for this gas is from tight, blanket gas basins such as the San Juan and Denver Basins.

** Base Case is defined as anticipated technological advances and gas production *without* an accelerated R&D program in enhanced gas recovery.

*** Price is stated in 1977 dollars and assumed maintained in constant dollars through the period of analysis; for example, a \$1.75 price under 6 percent inflation would need to be \$2.75 as expressed in 1985 dollars.

100 Tcf, accelerates the contribution of these resources by 1990 from 14 to nearly 22 Tcf, and raises the 1990 production rate from slightly over 2 to 3.5 Tcf.

TOTAL BASE CASE ESTIMATES (TCF)

	<u>Ultimate Recovery</u>	<u>Cumulative Recovery by 1990</u>	<u>Production Rate in 1990</u>
At \$1.75 per Mcf	70	14.4	2.3
At \$3.00 per Mcf	110	21.5	3.5

Raising price has a direct and significant effect on gas production from the Tight Gas Basins and the Devonian shale, but a similar price increase on its own is inadequate to initiate production from the other two areas addressed by the study -- Methane from Coal Seams and Methane from Geopressured Aquifers.

B. Advanced Case*

Considerable quantities of additional gas could be produced through successful R&D, directed toward improving understanding of the resource base and advancing the technology for recovering it. For this, the study posed an Advanced Case -- a set of evolutionary R&D goals that would expand the available geological targets, increase the recovery efficiency, and accelerate the exploitation of the unconventional gas resources.**

* The Advanced Case for unconventional sources includes the Base Case as well as additional stimulation by *accelerated public research* in enhanced gas recovery.

** Volume II of the study sets forth the explicit goals and timetable for reaching the Advanced Case.

Under the Advanced Case, at \$1.75 per Mcf, 150 to 160 Tcf could be ultimately added to domestic gas recovery from unconventional sources. Annual production would reach 6.6 Tcf in 1990.

TOTAL ADVANCED CASE ESTIMATES (TCF)

	<u>Ultimate Recovery</u>	<u>Cumulative Recovery by 1990</u>	<u>Production Rate in 1990</u>
• At \$1.75 per Mcf			
-- Total Advanced Case	150-160	38.0	6.6
-- Increment Over Base Case	80- 90	23.6	4.3
• At \$3.00 per Mcf			
-- Total Advanced Case	200-220	49.0	8.3
-- Increment Over Base Case	90-110	27.4	4.8

The greatest total production from unconventional resources, however, would accrue from a combination of improved economic incentives and advanced technology. At gas prices of \$3.00 per Mcf, 200 to 220 Tcf of unconventional natural gas could be ultimately recovered with substantial quantities, nearly 50 Tcf, available between now and 1990. This higher gas price combined with advanced technology will enable gas producers to develop the less productive parts of the Devonian shales in the Appalachian Basin, and provides a threshold price for beginning production of methane from coal and geopressured aquifers. In the tight gas basins, it enables industry to exploit the more difficult portions of the target.

C. Summary of the Potential of Unconventional Gas Sources

Under a successful R&D program, unconventional sources could make a substantial contribution to gas supplies, as shown in Exhibit 4.

- Under current technology and gas prices of \$1.75/Mcf, 70 Tcf could be recovered.
- Advanced technology, combined with a \$3.00/Mcf price, could increase the total to 200-220 Tcf.

Moreover, important amounts could be made available in the near-term. As Exhibits 5 and 6 show, the unconventional gas sources, already providing about 1 Tcf per year, could provide, under Advanced Technology and acceleration, from 3 to 4 Tcf in 1985, and from 6 to 8 Tcf in 1990 (at \$1.75 and \$3.00 per Mcf, respectively). Thus, unconventional sources of natural gas could be an important and economically attractive source for additional domestic source gas supplies.

Exhibit 4

The Potential of Gas from Unconventional Sources

* IN CONSTANT 1977 DOLLARS.

Exhibit 5

Total Domestic Gas Supply—Conventional and Unconventional Sources (at Gas Prices of \$1.75/Mcf and Current Technology)

Exhibit 6

The Potential of Unconventional Gas Sources Under Advanced Technology (at Gas Prices of \$3.00/Mcf ^{4/}

- 1/ RESERVES OF CRUDE OIL, NATURAL GAS LIQUIDS AND NATURAL GAS IN THE UNITED STATES AND CANADA AS OF DECEMBER 31, 1976, BY AGA/API/CPA.
- 2/ BASED ON A RECENT LEWIN AND ASSOCIATES, INC. STUDY, ANALYSIS OF THE TIMING AND TOTAL OF INFERRED RESERVES OF NATURAL GAS IN THE CONTIGUOUS UNITED STATES, BY J. BRASHEAR AND F. MORRA.
- 3/ BASED ON ONSHORE (LOWER 48) DISCOVERIES OF 1.0 TCF/YEAR AND OFFSHORE (LOWER 48) DISCOVERIES OF 0.5 TCF/YEAR, GROWING TO 3.9 AND 1.9 TCF RESPECTIVELY THROUGH DEVELOPMENTAL DRILLING.
- 4/ CONVENTIONAL SOURCE GAS IS ESTIMATED AT \$1.75 PER MCF.

V. GAS FROM UNCONVENTIONAL SOURCES -- A MORE DETAILED VIEW

The projection of new supplies of unconventional gas represents an aggregation from numerous sources, ranging from some near-conventional formations in the tight gas basins to the unexplored potential of geo-pressured aquifers. The resource base consists of four broad targets:

- Tight Gas Basins
- Devonian Shale
- Methane from Coal Seams
- Methane from Geopressured Aquifers

Exhibit 7 shows the contribution of these unconventional sources to domestic gas supply, at \$3.00 per Mcf under Base Case and Advanced Case technology, in terms of additions to ultimate recovery.

The following sections summarize the background and potential for each of these four unconventional gas resources.

A. The Potential of the Tight Gas Basins

The Tight Gas target consists of thirteen western and southwestern basins, as shown in Exhibit 8. They contain the original three Western Tight Gas Basins identified by the FPC, the large shallow gas area of the Northern Great Plains Province, and nine additional tight gas basins previously identified as being low permeability but analyzed for their first time in this study. The total gas in place in the probable and possible areas of these 13 basins is about 400 Tcf.*

* All speculative acreage in these basins was excluded from the current study.

Exhibit 7
Ultimate Recovery by Unconventional Target
(at \$3.00/Mcf)

Exhibit 8 Location of Major Tight Gas Basins

SOURCE: U.S. ERDA, WESTERN GAS SANDS,
PROJECT PLAN, 8/1/77

ERDA'S PRIMARY STUDY AREAS

GEOLOGICAL AREA

A. GREATER GREEN RIVER BASIN	TERTIARY AND CRETACEOUS
B. PICEANCE BASIN	TERTIARY AND CRETACEOUS
C. UINTA BASIN	TERTIARY AND CRETACEOUS
D. NORTHERN GREAT PLAINS PROVINCE	CRETACEOUS
E. WILLISTON BASIN	CRETACEOUS

ADDITIONAL LOW-PERMEABILITY AREAS IN THE STUDY

1. BIG HORN BASIN	TERTIARY AND CRETACEOUS
2. COTTON VALLEY TREND	JURASSIC
3. DENVER BASIN	CRETACEOUS
4. DOUGLAS CREEK ARCH	CRETACEOUS
5. QUACHITA MOUNTAINS PROVINCE	MISSISSIPPIAN
6. SAN JUAN BASIN	CRETACEOUS
7. SONORA BASIN	PENNSYLVANIAN
8. WIND RIVER BASIN	TERTIARY AND CRETACEOUS

OTHER LOW-PERMEABILITY AREAS NOT INCLUDED IN STUDY

a. ANADARKO BASIN	PENNSYLVANIAN
b. ARKOMA BASIN	PENNSYLVANIAN
c. FORTH WORTH BASIN	PENNSYLVANIAN
d. RATON BASIN	TERTIARY AND CRETACEOUS
e. SNAKE RIVER DOWNWARP	TERTIARY AND CRETACEOUS
f. WASATCH PLATEAU	CRETACEOUS
g. WESTERN GULF BASIN	TERTIARY AND CRETACEOUS

Production from the tight gas basins was found to be sensitive to increases in gas price and to advances in technology (Exhibits 9 and 10). Under current and near-term (Base Case) technology, industry is expected to produce substantial quantities of natural gas from these basins.

1. Base Case

- At \$1.75 per Mcf, nearly 70 Tcf will ultimately be recovered.
- Raising the gas price to \$3.00 per Mcf increases Base Case ultimate recovery by 30 Tcf, to about 100 Tcf; raising the price further adds little additional recovery.
- The 1990 annual production rate under the Base Case would range from 2 to 3 Tcf at gas prices of \$1.75 and \$3.00 per Mcf.

2. Advanced Case

- Improvements in the technology (the Advanced Case) further increase ultimate recovery:
 - At \$1.75 per Mcf, ultimate recovery under the Advanced Case is about 150 Tcf.
 - At \$3.00, the total ultimate recovery reaches 180 Tcf, and becomes relatively insensitive to price after this point.

Exhibit 9

Base and Advanced Case Ultimate Recovery at Three Prices

Exhibit 10

Annual Production from the Tight Basins to the Year 2000 (at \$1.75 and \$3.00 per Mcf)

- In addition to increasing ultimate recovery, technological advances also increase the annual rate of production:

- At \$1.75 per Mcf, the 1990 Advanced Case production rate is 6.3 Tcf, compared to 2.2 Tcf under the Base Case.
- At \$3.00 per Mcf, the Advanced Case production rate in 1990 is 7.7 Tcf, compared with 3.2 Tcf in the Base Case; higher prices beyond \$3.00 per Mcf add little to the 1990 production rate.

B. The Potential of the Devonian Shales -- Appalachian Basin

The Devonian shale resource target examined by the study consists of undrilled probable and possible areas in the Appalachian Basin. Starting with 210,000 square miles as the basin area, 100,000 square miles were judged to be barren of producible shale; 48,000 square miles were judged as speculative; 6,000 square miles have already been drilled or found non-productive -- leaving 56,000 square miles of shale deposit as the study area, shown as the central unshaded area in Exhibit 11. Within this area, the resource target is the free gas in place in the natural fractures and that can be placed in contact with the wellbore (using current as well as improved drilling and completion practices).

As in the tight gas basins, the amount of production and its rate are highly sensitive to gas price and technology. As shown in Exhibits 12 and 13, additions to ultimate recovery range from less than 2 Tcf at \$1.75

Exhibit 11

Geological Distribution of the Devonian Shales of the Appalachian Basin

Exhibit 12

Devonian Shale Ultimate Recovery (at Three Gas Prices)

Exhibit 13

Annual Production from the Devonian Shale to the Year 2000 (at \$1.75 and \$3.00 per Mcf)

under the Base Case, to possibly over 25 Tcf at \$4.50 per Mcf under the Advanced Case.

1. Base Case

- Nearly 2 trillion cubic feet of additional recovery will be economic at \$1.75 per Mcf.
- Increasing the price of gas to \$3.00 per Mcf would raise the recovery estimate to about 8 Tcf; at \$4.50 per Mcf, estimated ultimate recovery would be 10.5 trillion cubic feet.
- At \$1.75 per Mcf, the Base Case production rates would peak at 0.1 Tcf in 1990 and decline after that.
- At a higher price of \$3.00 to \$4.50 per Mcf, the 1990 rate would be about 0.3 Tcf. At \$3.00 per Mcf, a peak of 0.3 Tcf is reached in 1990, followed by a gradual decline; at \$4.50 per Mcf, production remains level through the year 2000.

2. Advanced Case

- Under the Advanced Case assumptions, ultimate recovery at \$1.75 increases to over 4 Tcf, from 2 Tcf in the Base Case.
- At \$3.00 per Mcf, ultimate recovery rises to 16 Tcf (versus about 8 Tcf in the Base Case).

- At \$4.50 per Mcf, ultimate recovery would range from 18 to 25 Tcf (the range reflects geological uncertainties in the possible areas where little is known about the intensity of the natural fracture system).
- Annual production under the Advanced Case and at \$1.75 per Mcf peaks at 0.3 Tcf in 1990, and declines thereafter.
- At \$3.00 per Mcf and the Advanced Case, 1990 annual production is estimated at more than 0.6 Tcf, holding constant through 1995, and declining thereafter; at \$4.50 per Mcf, the production rate continues to increase through the year 2000.

C. The Potential of Methane from Coal Seams

1. Methane Recovery Associated With Coal Mining

The initial target for recovering methane from coal seams is the 80 Bcf of methane emitted annually from working coal mines. No methane is currently recovered for commercial use -- all is vented, so there is no Base Case for this target.*

In general, the Appalachian Basin coal seams are too thin and too lean in methane content to economically support methane recovery on their own. Any estimates of recovery need to parallel closely the pace of mining

* I.e., it is assumed that all of the production benefits would be due to a joint public-private research and development program.

and the opening of new mines, thus providing only limited leeway in making production rate and recovery estimates.

Assuming a vigorous installation of methane emissions recovery facilities in the "gassy" coal mines, the following production benefits could accrue, at three prices for natural gas:

		Price Per Mcf		
		<u>\$1.75</u>	<u>\$3.00</u>	<u>\$4.50</u>
•	Ultimate (30 Year) Recovery, in Tcf	1.1	1.6	1.6
•	Yearly Production Rates, in Tcf/Year			
	1985	0.02	0.02	0.02
	1990	0.04	0.05	0.05
	1995	0.04	0.07	0.07
	2000	0.05	0.08	0.08
•	Cumulative Recovery by the Year 1990, in Tcf	0.2	0.2	0.2

2. Methane Recovery From Unminable Coalbeds

The major target for recovering methane from unminable coal seams would be the thick, bituminous coal seams of Colorado and the other Western states.

An economic analysis of methane recovery from deep, unminable coal seams using deviated wells provides the following estimates of recoverable methane as a function of natural gas price:

<u>Price/Mcf</u>	<u>Recoverable Methane (Tcf)</u>
\$1.75	0 - 10
\$3.00	0 - 20
\$4.50	0 - 25

Due to the speculative nature of the resource base and the uncertain capacity of existing technology to exploit it economically, only a range of estimated recovery can be made at this time. No estimates have been made of production rates. All of the recovery is assumed to accrue from a joint public-private research and development program, as there is little evidence of Base Case activity.

D. The Potential of Methane from Geopressured Aquifers

Large water-bearing reservoirs characterized by significantly higher temperatures and pressures than their depth alone would suggest lie deep beneath the Gulf of Mexico and the coastal regions of Texas and Louisiana. These are referred to as geopressured aquifers. Under these conditions, considerable methane may be dissolved in the trapped water, particularly if the water is low in salinity.

Although estimates of the gas in place in such reservoirs have been large, the essential question is not the total size of the resource but the portion that may be technically and economically recoverable.

Economic analysis of the available data on the geopressured resource base* provides the following estimates of economic potential from geopressured aquifers as a function of gas price, shown below (in Tcf):

	<u>Texas</u>	<u>Louisiana**</u>
Technically Recoverable Gas in Place	2	40
Economically Recoverable Gas at:		
\$1.75/Mcf	-	-
\$3.00/Mcf	0.1	1.0
\$4.50/Mcf	0.4	5.0

Due to the very preliminary state of development of this resource, no production rates have been projected. It is unlikely that these resources will be developed without continued, active collaborative Federal-industry research and development.

-
- * Beyond the quantities estimated from using available resource data, still deeper horizons may exist in Texas and central Louisiana. Further, the research work on geopressured methane has intimated a second resource target that may be associated with geopressured aquifers -- free methane in excess of that in the saturated reservoir brines. Should either of these conditions be proved by further research, the economic potential of geopressured aquifers may substantially increase.
- ** The resource data for Louisiana is considered speculative, since little conclusive data are available on areal size or permeability of the south Louisiana geopressured aquifers. Optimistic assumptions have been used for the unknown parameters in estimating the above recoveries.

VI. TRADE-OFF ANALYSIS

One of the more critical choices faced by energy policy makers involves the trade-off between using market forces (prices and taxes) and improved technology for augmenting domestic supplies of natural gas.

For the unconventional gas sources, higher price (or other improvements in economic incentives) can substitute for improved technology, but only up to a limit. Using economic incentives alone, however, appears to provide less than the optimum public policy choice. An advanced technology strategy, at either \$1.75 per Mcf or \$3.00 per Mcf, is a preferred choice.

1. The Advanced Case provides substantially more gas and thus is preferable to the Base Case at all examined gas prices.

<u>Price/Mcf</u>	<u>BASE</u>		<u>ADVANCED</u>	
	<u>Ultimate Recovery</u> (Tcf)	<u>1990 Production Rate</u> (Tcf/Year)	<u>Ultimate Recovery</u> (Tcf)	<u>1990 Production Rate</u> (Tcf/Year)
\$1.75	70	2.3	150-160	6.6
\$3.00	110	3.5	200-220	8.3
\$4.50	120	3.8	210-240	8.5

2. An Advanced Technology strategy in combination with a gas price of up to \$3.00 per Mcf offers a large amount of gas at a relatively low cost to the public.

- Under the Base Case, 3.5 Tcf per year would be produced in 1990; ultimate recovery would be 110 Tcf, with 22 Tcf being produced by 1990.

- Under the Advanced Case, the production rate from unconventional sources could reach 8 Tcf per year in 1990. Ultimate recovery would be 200 to 220 Tcf, with nearly 50 Tcf being produced by 1990. The energy cost to the public would be \$600 to \$660 billion ultimately.
- Obtaining comparable quantities of gas from other sources would impose a higher energy cost on the public and place additional pressure on the balance of payments. Even assuming comparable quantities could be obtained at \$4.00 to \$5.00 per Mcf,* the energy cost to the public would be \$800 to \$1,100 billion ultimately, with significant portions being paid to other governments, at least in the initial years.

These findings are shown on the table below.

	<u>Additions to Domestic Gas Supply</u>		<u>Energy Cost to the Public</u>	
	<u>by 1990</u>	<u>Ultimate</u>	<u>by 1990</u>	<u>Ultimate</u>
	(Tcf)		(Billions)	
• Advanced Case Enhanced Gas Recovery (at \$3.00 per Mcf)	50	200-220	\$150.4	\$600-660
• Substitute Energy Case (@ \$4.00 to \$5.00 per Mcf)	50	200-220	\$200-250	\$800-1100

* Assuming imported gas at \$2.50 to \$3.00 per Mcf, Alaskan gas at \$3.00 to \$5.50 per Mcf (including transportation), LNG imports at \$4.50 per Mcf, coal gasification at \$4.50 to \$5.50 per Mcf. The analysis of supplies from conventional gas resources due to higher prices were beyond the scope of this study.

3. An Advanced Technology strategy is more cost-effective than using economic subsidies in excess of real market prices.

The analysis in the preceding section was bounded by market level prices for natural gas of up to \$3.00 per Mcf. However, as in the case of imported LNG, the government could consider a price of \$4.50, and thus a subsidy of up to \$1.50 per Mcf,* to stimulate production from unconventional gas sources.

- The analysis under the Base Case shows only very limited price elasticity between \$3.00 to \$4.50 per Mcf -- total supply increases by only 10 Tcf, from 110 to 120 Tcf -- and at a high cost to the public.
- The analysis of the Base Case is based on empirical evidence and projections that have been built on evolutionary changes in gas prices up to about \$3.00 per Mcf. At higher gas prices (particularly should these higher prices be guaranteed or subsidized), it is likely that industry will increase its near-term investment in R&D and thus accelerate the production of the unconventional sources.
- Under this case, one can defer public investment in R&D. However, in return, this will impose a large cost, \$180 to \$360 billion, to the public.

* Again, the price of gas (or its economic equivalent) is expressed in 1977 dollars and held constant for the period of analysis; a \$4.50 price in 1977, held constant with respect to 6% inflation, would be \$7.20 in 1985 dollars and the \$1.50 subsidy would be \$2.40.

At these prices, gas recovery could range from 120 to 240 Tcf, depending on how industry's R&D initiatives respond to the price incentives.

- Stimulating a \$0.4 billion investment in R&D to obtain 200 to 220 Tcf (assuming a market price of \$3.00 per Mcf) is more cost-effective and certain than spending \$180 to \$360 billion in public subsidies to obtain 120 to 240 Tcf (assuming a subsidy of \$1.50 per Mcf over the same market price of \$3.00 per Mcf).

These findings are shown on the table below.

<u>Policy Alternatives</u>	<u>Ultimate Recovery (Tcf)</u>	<u>Additional Cost to the Public (Billions)</u>
R&D with a \$3.00/Mcf Market Price	200-220	\$0.4*
Public Economic Subsidy of \$1.50/ Mcf Over a \$3.00/Mcf Market Price	120-240	\$180-\$360

4. In summary, the findings of the study of enhanced gas recovery from unconventional sources show:

- Market forces and public investment in R&D are a direct trade-off for *near-conventional* gas resources. Either higher price or improved recovery technology with a lower price would cause these resources to be produced.

* Assuming a \$370 million investment in R&D to advance the technology.

- Publicly or privately directed R&D is the essential mechanism for stimulating additional gas from *unconventional* sources. Higher prices could stimulate private R&D in the unconventional areas and thus ultimately unlock these sources; however, a focused and coordinated 5 year R&D program would most efficiently accelerate production during the time of greatest potential gas shortage.
- Overall, a combination of economic incentives* and R&D appears to provide the optimum public policy option for stimulating production from unconventional sources of gas:
 - Using a "price alone" strategy would provide from 2 to 4 Tcf per year by 1990.
 - Using an "R&D strategy" in combination with price incentives could provide as much as 8 Tcf per year by 1990.

* The study of enhanced gas recovery examined only three prices -- \$1.75, \$3.00, and \$4.50 per Mcf -- and an optimum research program for a given price. It did not seek to establish the optimum price or optimum combination of public R&D and price.

PART II

THE PROPOSED RESEARCH STRATEGY IN ENHANCED GAS RECOVERY

- Proposed R&D Plan
- R&D Costs
- Production Benefits
- Cost-Effectiveness of the Research Program
- Need for Additional Options

THE PROPOSED RESEARCH STRATEGY IN ENHANCED GAS RECOVERY

A. Proposed R&D Plan

The overall objectives of the research plan are to define the unconventional gas resources, to advance the state of the technology so as to economically exploit these resources, and to optimize and accelerate the emerging recovery technology.

The proposed five year program consists of 16 major programs across the four unconventional gas resource bases, as shown below:

<u>Unconventional Resource Base</u>	<u>Title of the R&D Program</u>	<u>No. of Programs</u>
1. Tight Gas Basins	• Resource Evaluation and Characterization	3
	• Develop Advanced Recovery Technology	4
	• Optimize Recovery Technology	2
	• Stimulate Accelerated Application	2
2. Devonian Shale	• Develop Deep, High Cost Formations	1
	• Test Potential of Dual Completions	1
	• Improve Recovery Efficiency	1
3. Methane from Coal	• Recover Methane in Association with Mining	1
	• Recover Methane from Unminable Coal Seams	1
4. Geopressured Aquifers	• Ascertain Reservoir Size, Methane Content, and Production Technology	1

B. R&D Costs

Unlocking the potential of these diverse unconventional sources of natural gas will require a concerted program of research, development, and demonstration. In addition to on-going industry outlays, nearly \$370 million additional is required over the next five years. While numerous mechanisms are available for accomplishing this task, one mechanism is joint Federal-industry cost-shared research programs in enhanced gas recovery.

- The yearly costs for the 5-year DOE/Industry joint research program are as follows (in millions of constant 1977 dollars):

	<u>Total Costs</u>	<u>DOE Share</u>
Total 5-Year Costs (FY 79-FY 83)	\$369.1	\$265.5
Yearly Costs:		
FY 79	\$ 59.7	\$ 45.5
FY 80	80.7	60.4
FY 81	74.6	53.5
FY 82	87.0	56.3
FY 83	67.1	49.8

- An analysis of the 5-year R&D program shows that public R&D (the DOE share) funds the resource characterization, improved measurement, and technology transfer program elements; DOE and industry jointly fund the field-based R&D.

<u>Program Elements</u>	<u>Tight Gas Reservoirs</u> (Total/DOE)	<u>Devonian Shale</u> (Total/DOE)	<u>Methane from Coal</u> (Total/DOE)	<u>Methane from Geopressured Aquifers</u> (Total/DOE)	<u>TOTAL</u> (Total/DOE)
Resource Characterization	\$ 37.9/37.4	\$6.5	\$5.5	\$2.7	\$ 52.6/52.1
Improved Measurement	15.2	2.5	2.0	3.0	22.7
Field Tests	188.1/98.0	27.1/19.1	36.5/31.5	30.0	281.7/178.6
Technology Transfer	<u>8.0</u>	<u>2.0</u>	<u>1.6</u>	<u>0.5</u>	<u>12.1</u>
TOTAL	\$249.2/158.6	\$38.1/30.1	\$45.6/40.6	\$36.2	\$369.1/265.5

C. Production Benefits

Successful execution of the proposed R&D program could lead to the required advances in technology and in turn to additional gas recovery and acceleration of its production.

Two measures were used to quantify these benefits:

- A long-term measure of additions* to ultimate recovery (at \$3.00 per Mcf) over that due to Base Case technology.
- A near-term measure of additional gas that can be produced between now and 1990 (at \$3.00 per Mcf) due to advanced technology.

The estimated additional recovery, over the Base Case, is shown below:

	Long-Term Measure Ultimate Addition to Recovery	Near-Term Measure Cumulative Addition to Recovery: 1978-1990
	(Tcf @ \$3.00/Mcf)	(Tcf @ \$3.00/Mcf)
Tight Gas Sands	81	25
Devonian Shale	8	2
Methane from Coal Seams	2-22	N/A**
Methane from Geopressured Aquifers	<u>1</u>	<u>N/A***</u>
TOTAL	92-112	27

* These are additional quantities, over the Base Case, that would accrue due to successful R&D leading to the Advanced Case.

** 1990 cumulative recovery estimates are available only for a portion of the Methane from Coal Seams target.

*** 1990 cumulative recovery estimates are not available for the Methane from Geopressured Aquifers target.

D. Cost-Effectiveness of the Research Program

An essential question facing officials responsible for allocating public funds is: "How cost-effective is the expenditure?". Using the two production benefit measures discussed above, the analysis indicates that the payoff from R&D in enhanced gas recovery is considerable and cost-effective:

- The long-term cost-effectiveness measure for all sixteen programs combined is 250 to 300 Mcf per dollar of R&D.
- The near-term overall cost-effectiveness measure is 70 Mcf per dollar of R&D.

Individually, each of the target areas also have favorable cost-effectiveness ratios:

<u>Unconventional Gas Target</u>	<u>Ultimate Measure (Mcf/\$)</u>	<u>Near-Term Measure (Mcf/\$)</u>
Tight Gas Sands	320	100
Devonian Shale	210	50
Methane from Coal Seams	40-500	N/A
Methane from Geopressured Aquifers	30	N/A

Assuming that the nation requires additional natural gas from domestic sources, as the analysis above argues, and that a price of \$4.00 to \$5.00 per Mcf is required for other substitute sources, such as imported gas, LNG, coal gasification, or electricity, the trade-off to the public is:

- 250 to 300 Mcf per dollar* for R&D in enhanced gas recovery (EGR).
- Less than 1 Mcf per dollar** of public outlays for substitute sources of natural gas or energy.

The analysis shows that funds invested in EGR are considerably more cost-effective than seeking the same quantities through substitute sources of gas or other energy.

E. The Need for Additional Options

For an equivalent amount of energy between now and 1990, the unconventional gas sources under advanced technology and at \$3.00 per Mcf provide as low or lower cost to the public than any substitute energy source. However, even with these additions to supply, the projections above show that gas supply remains below 1977 usage levels. Thus, additional gas supply programs, such as LNG, coal gasification, electricity, and gas imports, though costly, are required to fill the gap and provide the nation with adequate energy supplies.

* Assuming 100 Tcf can be obtained at \$3.00 per Mcf and \$370 million of R&D in enhanced gas recovery.

** Assuming 100 Tcf can be obtained at \$4.50 per Mcf and no R&D; this is equivalent to a \$3.00 per Mcf market price plus \$1.50 per Mcf public subsidy.

PART III
METHODOLOGY

METHODOLOGY

A. Purpose for the Study

This study of enhanced recovery of unconventional gas was undertaken for two reasons:

1. To provide quantitative information on the potential and economic feasibility of producing four sources of unconventional natural gas -- Tight Gas Sands, Devonian Shales, Methane from Coal Seams, and Geopressured Aquifers.
2. To provide analysis and insights as to the technical barriers posed by these resources, including technological interventions that could "unlock" their potential.

This information has been gathered to assist DOE managers select and design a cost-effective program of enhanced gas recovery.

B. Analytic Methodology

The analysis seeks to simulate, at a planning model level, how gas producers evaluate prospective opportunities (Exhibit 14). It begins with geologic data and well records, provides estimates of gas production, evaluates economic feasibility, and, where feasible, develops the prospect according to an orderly drilling schedule -- in brief, it follows an engineering-economics-geologic approach. The principal features of this approach are described briefly below and in greater detail in Volume III.

EXHIBIT 14

Simplified Flow Diagram of the EGR Analysis

Geology and Well Data

Reservoir Characteristics
Technology Specification

- Base Case
- Advanced Case

Cost Data
Gas Price

Areal and Success
Rate Data

Production
Simulation

Production profile per formation:

- Base Case
- Advanced Case

Project Economics
Model

Economic production per well:

- All prices
- Base Case
- Advanced Case

Extrapolation and
Timing Model

Expected ultimate production and
production rates, all prices:

- Base Case projection
- Advanced Case projection
- Increment of Advanced over Base — Program Benefits
- Requirements for production

1. Collection of Geologic and Well Data. More than fifty geologists and engineers from industry, consulting firms, and government agencies assisted in collecting data on the unconventional gas resources. This data included geologic studies, completion and recovery performance of individual wells, stimulation test results, and exploration success data.

2. Selecting and Defining the Resource. Based on the geologic and well data, the total area of each relevant basin was divided into four segments:

- Proved -- already proved by drilling and under development.
- Probable -- areas adjacent to proved areas where extension development is likely.
- Possible -- outlying areas in which there has been sufficient historical drilling to establish gas "shows", although perhaps not economic wells.
- Speculative -- areas in the basins which are undrilled, in which drilling has yet to reveal gas deposits, or where quality data was lacking.

Only "probable" and "possible" areas were included in the analysis. Proved areas were excluded because their production is part of the currently proved reserves. Speculative areas lacked sufficient data to support an engineering-economics evaluation.

The reservoir properties of the target geologic formations in these areas were analyzed in detail. The areas were divided into sub-basins and subdivided into vertically stacked geologic formations in each areal unit, as follows:

<u>Resource</u>	<u>Analytic Units</u>
Tight Gas Basins	622 reservoirs
Devonian Shale	34 areal units
Methane from Coal Seams	
-- with mining	Appalachian Region
-- unminable	All unminable coalbeds
Methane from Geopressured Aquifers	23 fairways and horizons

3. Technology Specification. Two levels of technology were specified -- Base Case and Advanced Case. The Base Case definition was derived from the actual field experience of industry and the R&D efforts planned by industry for the next five years. This level of technology was specified, for each of the four resources, in levels of performance (e.g., fracture length, fracture conductivity, etc.).

The Advanced Case was defined as the level of performance that could be achieved from a successful R&D program.

4. Production Simulation. The detailed reservoir and geologic data were combined with the explicit technology specifications to develop estimates of gas production.

- For the Tight Sands, a state-of-the-art reservoir simulator, developed at Texas A&M University, was used to model the gas production from each reservoir unit as a function of reservoir properties and technology.

- Production estimates for the Devonian Shale were based on area-specific, historic production data, adjusted to reflect advances in technology. The A&M reservoir simulator was used to provide supportive and validating analyses.
- Production from unminable coalbeds was based on the rate of mining and methane capture. From unminable coalbeds, recovery estimates were made by combining an analytic diffusion model with average reservoir characteristics and methane content of the coal.
- Estimates of production from geopressured aquifers were based on reservoir flow models using estimated methane content and reservoir properties.

5. Project Economics Model. Production data were combined with field cost data to assess the economic feasibility of each analytic unit. For the Tight Sands and Devonian Shale, the method was a discounted net present value (NPV) cash flow model using field development and stimulation costs (updated to 1977). A payback model was used for methane from coalbeds and geopressured aquifers. The costs varied by field according to location, depth, and technology. Economic viability was examined at gas prices of \$1.75, \$3.00, and \$4.50 per Mcf, in 1977 dollars.

6. Extrapolation and Timing Model. Economic projects were developed in a phased progression across the probable and possible portions of each sub-basin. This defined the number of wells to be drilled and the time-phased rate of expansion across each basin. Probable areas were assumed

to be drilled prior to possible areas. Production from the Base and Advanced Cases, respectively, was aggregated to provide the overall recovery estimates and to define the incremental benefits for each R&D strategy.

In summary, the Analysis Phase was designed to approximate corporate processes for evaluating the potential of the unconventional resources -- their geologic and reservoir parameters, productive potential, economic viability, and development -- in light of alternative technology levels and gas prices.

C. Use of Analysis

The analytic phase of the study provided information for two subsequent DOE steps in establishing the R&D program in enhanced gas recovery:

- Designing realistic, achievable R&D strategies and plans for each resource.
- Selecting a mix of cost-effective R&D strategies and plans across the unconventional gas resources.

- Improving technology and resource characterization
- Proving the economics
- Accelerating field application

As these three goals are achieved, enhanced recovery can substantially increase gas supply from unconventional gas sources and thus provide a highly cost-effective near-term as well as long-term program.

Using a combination of economic incentives and publicly sponsored R&D, the unconventional gas sources could provide 200 to 220 Tcf of additional gas supply, as shown on Exhibit 1:

- The contribution of the unconventional sources, even under current technology and gas price of \$1.75/Mcf, is substantial -- 70 Tcf.
- Introducing advances in the technology increases the total to 150-160 Tcf.
- Combining a price of \$3.00/Mcf (or its economic equivalent) with advanced technology raises the potential of gas from unconventional sources to 200-220 Tcf -- equal to current domestic proved reserves.

Moreover, substantial quantities of this gas could be delivered in the near term -- as much as 2 Tcf to 8 Tcf per year by 1990, depending on the specific economic and technologic mix selected by public officials.

PART IV

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