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TECHNICALLY RECOVERABLE DEVONIAN SHALE GAS IN OHIO

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P.O. Box 880
Morgantown, West Virginia 26505

By
Vello A. Kuushraa and Donald E. Wicks
Lewin and Associates, Inc.
1090 Vermont Ave., N.W., Suite 700
Washington, D.C. 20005

Walter K. Sawyer
Mathematical and Computer Services, Inc.

Patrick R. Esposito, Ph.D., P.E.
Engineering Decision Consultants, Inc.

DISCLAIMER

PREFACE

This report is a technical integration effort to estimate the technically recoverable gas resource of the Devonian Shale formation in Ohio. Results are based on the integration of the most recent data and research that evolved in the Eastern Gas Shales Subprogram which makes up a significant part of DOE's Research in Unconventional Gas Recovery Program. Specifically the information used in this study includes: (1) a compilation of the latest geologic and reservoir data for the gas in place; (2) analysis of the key production mechanisms; and (3) examination of alternative stimulation and production strategies for most efficiently recovering this gas.

The general approach taken in this study builds on the existing knowledge gained in the last six years and, in particular, from several important summary type documents recently concluded under the sponsorship of DOE/METC. These documents include:

- Mound Lab Report -- geochemistry of the Appalachian Basin
- Cliffs Minerals Report -- natural fracture systems in the Appalachian Basin
- DOE's offset well report - reservoir properties in Ohio

In addition, gas production and open flow data that became available as public information from the recent upsurge of drilling in the Appalachian Basin are used to supplement the primary sources.

The objective of this study is to integrate all of the known information into a useful summary document covering broad regions. It is an attempt to synthesize acquired data on a high enough level to help industry in their decision making process on where to drill and how to extract for shale gas once the market and gas price warrant new ventures. It should be noted that no attempt was made to quantify the risks and uncertainities associated with shale well drilling ventures. This analysis is the responsibility of the investor/producer group. Accordingly, this report was prepared as a good reference document from which to work.

Project Management
Eastern Gas Shales

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ABSTRACT

The technically recoverable gas from Devonian shale (Lower and Middle Huron) in Ohio is estimated to range from 6.2 to 22.5 Tcf, depending on the stimulation method and pattern size selected.

This estimate of recovery is based on the integration of the most recent data and research on the Devonian Age gas-bearing shales of Ohio. This includes: (1) a compilation of the latest geologic and reservoir data for the gas in-place; (2) analysis of the key productive mechanisms; and, (3) examination of alternative stimulation and production strategies for most efficiently recovering this gas.

Beyond a comprehensive assembly of the data and calculation of the technically recoverable gas, the key findings of this report are as follows:

- A substantial volume of gas is technically recoverable, although advanced (larger scale) stimulation technology will be required to reach economically attractive gas production rates in much of the state;
- Well spacing in certain of the areas can be reduced by half from the traditional 150 to 160 acres per well without severely impairing per-well gas recovery; and,
- Due to the relatively high degree of permeability anisotropy in the Devonian shales, a rectangular, generally 3 by 1 well pattern leads to optimum recovery.

Finally, although a consistent geological interpretation and model have been constructed for the Lower and Middle Huron intervals of the Ohio Devonian shale, this interpretation is founded on limited data currently available, along with numerous technical assumptions that need further verification.

SUMMARY

PURPOSE OF THE STUDY. This study integrates past research and current data in developing an estimate of technically recoverable gas resources for the Devonian shales of Ohio. In so doing, the study has had to grapple with the key (and often difficult) technical issues imbedded in such an analysis, including:

- How to properly characterize and interpret the major production mechanisms that govern the flow of gas in the Devonian shales;
- How to use secondary geologic/reservoir measures to define gas potential areas;
- What types of well stimulation techniques to apply in the various geological settings; and
- How to reliably simulate, through reservoir models, the gas flow rates, and to optimize ultimate gas recovery?

This report builds and improves on the technologic knowledge base to provide a scientific understanding of the Devonian shale gas resource. It's primary audience is intended to be explorationists, geologists, and R&D managers interested in a detailed basin level anlysis of the resource, along with independent operators interested in choosing a stimulation technique in a given area.

The purpose of this study is to examine these issues in broad regional settings. Therefore, the findings of this study are not intended to be representative of any specific lease area or well location.

METHODOLOGY. The study methodology consisted of eight steps:

1) Identification of Consistent Geologic/Reservoir Data.
Several reservoir parameters, such as matrix permeability and porosity, were found not to vary widely and thus were kept

constant over the study area. The reservoir data and parameters were assembled from:

- Historical gas production and well records,
- The EGSP core well program, and
- The Offset Well Test Program (Meigs County, Ohio).

2) Development of Variable Geologic Data By County. Reservoir parameters that showed strong regional variation, such as gas content and pressure, were developed for each county from actual data or were extrapolated from a series of isoline maps developed for Ohio. This data was based on:

   - Geological and geochemical reports by Cliffs Minerals and Mound Facility;

   - Fracture conductivity studies by Terra Tek;

   - Stress-ratio maps prepared by U.S. Department of Energy's Morgantown Energy Technology Center; and

   - Rock pressure data from 257 wells in 15 counties.

3) Assembly of Actual Gas Production Data. Historical gas production data for Ohio were gathered from state and company records, as follows:

   - Long-term production data were assembled from 108 wells in 11 counties; and

   - Initial open flow (24 hr.) data were collected from 222 wells in 12 counties.

The location and concentration of these data are shown on Exhibit 1.

4) History Matching of Production Data and Productive Interval. A reservoir simulator entitled Simulator for Unconventional Gas Recovery (SUGAR) was used to match production data and back-calculate the remaining unknown reservoir parameters of fracture permeability and net productive interval, as well as to ensure consistency in the basic data.

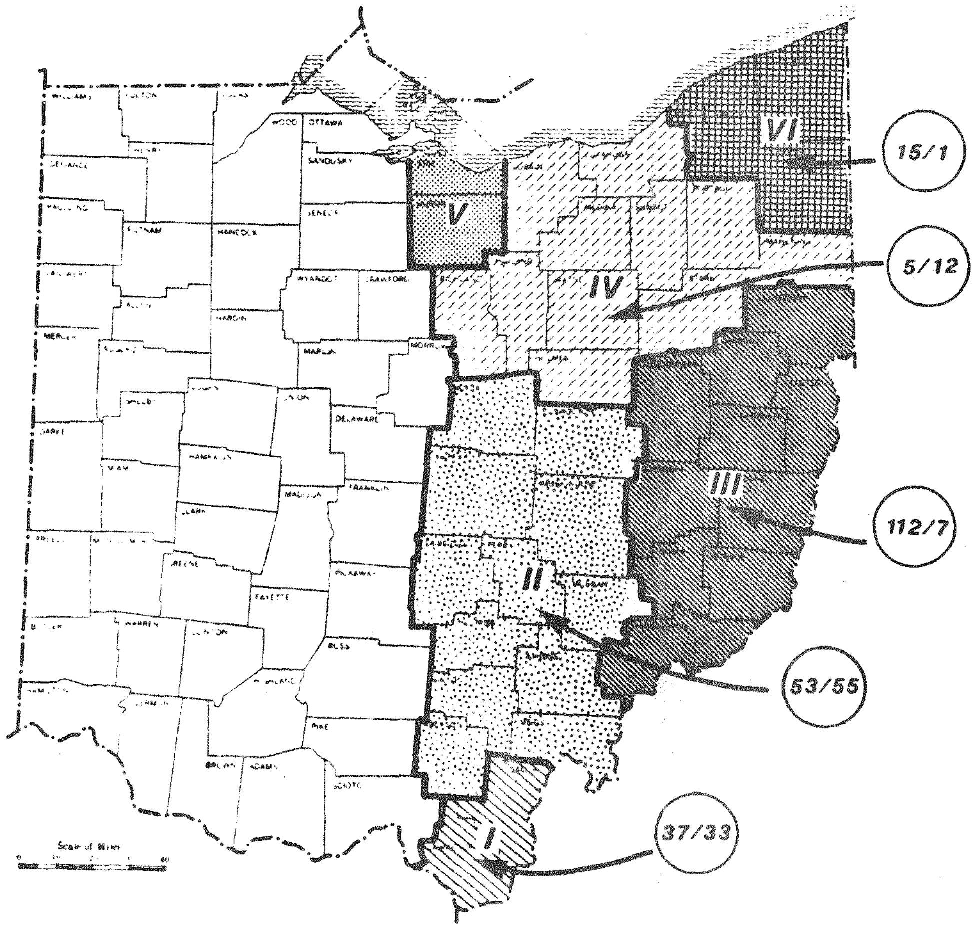
5) Definition of the Fracture Regimes. Beyond the data required for analyzing the performance of well stimulation by borehole shooting, additional geological data were required to properly evaluate well performance with improved stimulation technology. These additional data included:

- Determining directional components of fracture permeability to reflect permeability anisotropy;
- Identifying the expected angle of intersection between induced and natural fractures to estimate whether the induced fracture will cross or terminate in the natural fracture system; and
- Establishing an optimal well drainage geometry to best match permeability anisotropy and stimulation method.

6) Development of Six Regional Partitions for Ohio. Gas production estimates were made for each county using the geological and production data developed in Steps 2 through 5, above. The state of Ohio was then partitioned into six overall areas (partitions) based on 40-year cumulative gas production, and the key geological parameters and tectonophysics that establish the natural stress and fracture regimes, as shown on Exhibit 1.

Exhibit 1

PRIMARY PARTITIONED AREAS
DEVONIAN GAS SHALES OF OHIO



#/ NUMBER OF OPEN-FLOW GAS PRODUCTION RECORDS
/# NUMBER OF LONG-TERM GAS PRODUCTION RECORDS

AVERAGE GEOLOGIC PROPERTIES BY AREA

PARTITIONED AREA	FRACTURE SPACING (feet)	PERMEABILITY ANISOTROPY (ratio)	INTERSECTION ANGLE (degrees)
I	10	1:1	N/A
II	20	6:1	10
III	20	4:1	20
IV	20	6:1	40
V	20	8:1	40
VI	20	8:1	40

7) Development of Representative Data by Partitioned Area. The essential geological data were aggregated and compiled by each of the six partitioned areas, as summarized on the bottom of Exhibit 1.

8) Delineation of Alternative Stimulation Cases. Four well stimulation techniques, beyond traditional borehole shooting, were evaluated:

- Small Radial Stimulation (r'_w = 30 feet): attainable with emerging technological improvements in omni-directional stimulation;

- Large Radial Stimulation (r'_w = 60 feet): potentially attainable with major improvements in explosive and propellant technology;

- Small Vertical Fracture (x_f = 150 feet): attainable, but not yet fully controllable or predictable with current technology; and

- Large Vertical Fracture (x_f = 600 feet): potentially attainable with significant advances in technology or alternate fracture fluids and proppants.

The results of the analysis were then assembled according to a Base Case that examined gas production using borehole shooting, and a series of Advanced Cases that examined the effects of using the above more-extensive well stimulation treatments.

SUMMARY OF FINDINGS. Six major findings emerge from this study:

1. Based on Geologic Characteristics, Tectonophysics, and Simulated Gas Production, the State of Ohio Was Partitioned Into Six General Areas. These areas have been ranked by production, as Areas I to VI and are shown on Exhibit 1.

2. The Devonian Shales of Ohio Offer a Major Source of Technically Recoverable Natural Gas. Recoverable gas in Ohio was estimated for each of the six partitioned areas, Exhibit 2. In total, recoverable gas ranges from 6.2 to 15.2 Tcf over 40 years (depending on stimulation) from wells drilled on 160-acre spacing in the Middle and Lower Huron members. Average production per well was found to be highest in southern Ohio (Area I) and to generally decline northeastward over the state.

3. It Will Take a Major Drilling Effort, From 44 to 88 Thousand Wells, to Produce the Technically Recoverable Gas. Given an undrilled, accessible area of nearly 11,000 square miles (7 million acres), it would take 43,970 wells on 160-acre spacing, or 87,940 wells on 80-acre spacing, to fully develop and produce the technically recoverable gas in Ohio from the target intervals.

4. Improved Stimulation Technology is Required to Unlock the Full Gas Potential. Use of large vertical fractures, in the high gas potential Area I, will provide per well cumulative recoveries (over 40 years) of 1,080 MMcf versus 386 MMcf by borehole shooting. Even in the low gas potential Area VI, large radial stimulation would more than double the gas flow rates and ultimate recovery, as compared with borehole shooting. Other advances, for more efficiently interconnecting the full natural fracture system to the wellbore, would further increase gas recovery.

5. <u>Alternative Well Spacing and Pattern Configuration Will Help Increase Recovery</u>. Reduced well spacing to 80 acres per well will also increase gas recovery (from 15.2 Tcf at 160 acres to 22.5 Tcf at 80 acres) without appreciably reducing gas recovery in the initial years. In addition, when using one of the improved stimulation methods, changing the pattern alignment to a 3 by 1 rectangle instead of a square will add from 5 to 10 percent recovery per well.

6. <u>A Considerable Amount of Geological/Geophysical Data is Required to Properly Simulate the Gas Production Mechanism of the Devonian Shales</u>. Beyond the conventional gas storage and production mechanisms, the major controlling factors in the Devonian shale include fracture permeability and intensity, permeability anisotropy, adsorbed gas, the capacity to connect the natural fracture system to a wellbore, and the difficult-to-measure (by conventional means) net productive interval. While recent work has begun to provide some of this data, a considerable amount of extrapolation and reliance on assumption was required for this study. Substantial future research and drilling is required to further increase the understanding of gas production from Devonian shales.

* * * * *

Exhibit 2 provides a summary of the gas in-place and technically recoverable gas, by area and stimulation method. The fact sheets which follow this exhibit present further detail on the reservoir properties, gas potential, cumulative gas recovery, and production decline curves for the six partitioned areas of Ohio.

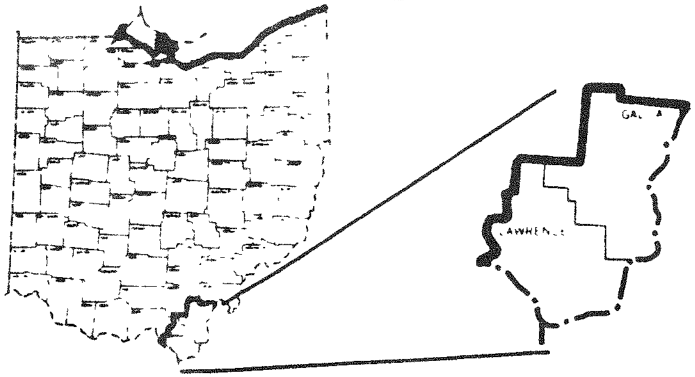
Exhibit 2

TECHNICALLY RECOVERABLE GAS, BY AREA AND STIMULATION METHOD

			TECHNICALLY RECOVERABLE GAS (TCF) IN 40 YEARS				
PARTITIONED AREA	TOTAL DRILLABLE AREA (SQ. MI.)	GAS IN PLACE (TCF)	BOREHOLE SHOOTING	SMALL RADIAL STIMULATION $r'_w=30'$	LARGE RADIAL STIMULATION $r'_w=60'$	SMALL VERTICAL FRACTURE $X_f=150'$	LARGE VERTICAL FRACTURE $X_f=600'$
I	543	4.1	0.84	1.16	1.41	1.58	2.35
II	3,577	12.4	2.95	4.06	4.64	4.67	6.21
III	2,869	4.4	1.46	1.98	2.25	2.33	3.04
IV	2,641	24.8	0.84	1.35	1.73	1.78	3.38
V	313	0.4	0.05	0.06	0.06	0.06	N.A.
VI	1,035	3.3	0.04	0.07	0.10	0.09	0.20
TOTAL	10,978	49.4	6.18	8.68	10.19	10.52	15.18

SUMMARY OF OHIO DEVONIAN SHALE GAS POTENTIAL

AREA I



BASIC DATA

KEY RESERVOIR PROPERTIES

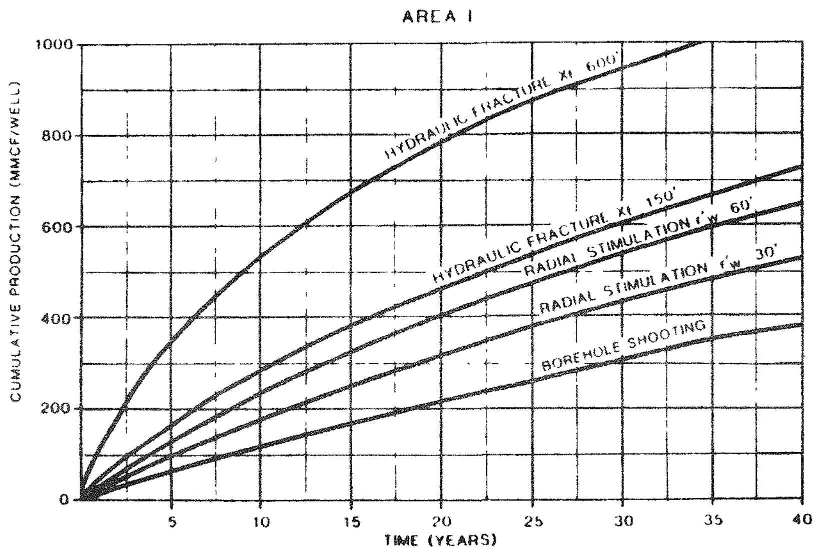
• DEPTH (ft)	2320
• ROCK PRESSURE (psig)	690
• GAS CONTENT (Mcf/AF)	100
• "NET" THICKNESS (ft.)	119
• FRACTURE PERM (md)	.0276
• INIT. OPEN FLOW (Mcf/D)	49
• PERM ANISOTROPY (ratio)	1:1
• FRACTURE INTERSECTION ANGLE (°)	N/A
• FRACTURE SPACING (ft)	10

GAS POTENTIAL

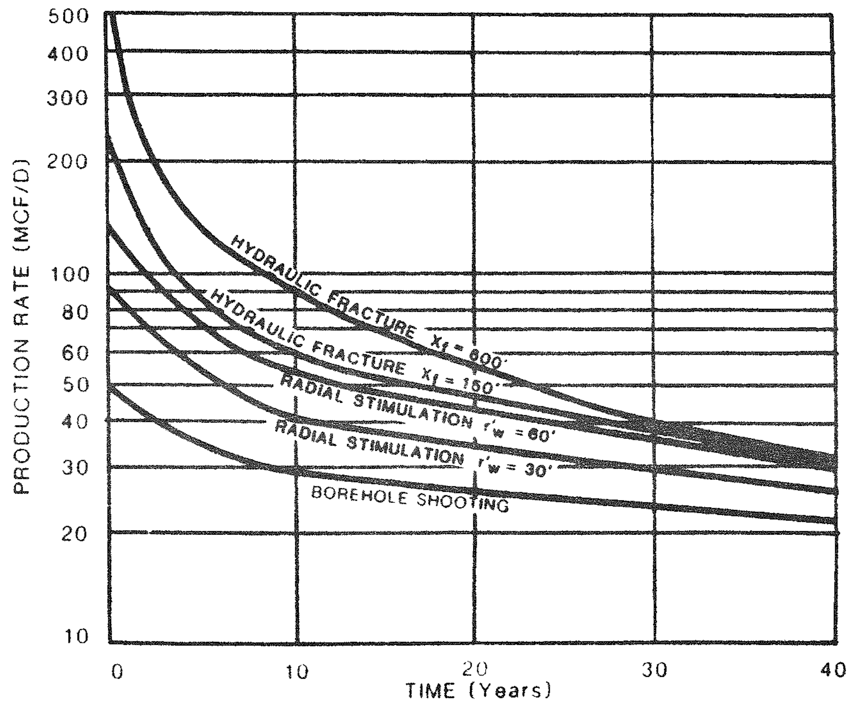
• DRILLABLE AREA (ACRES)	347,520
• RECOVERABLE GAS w/ BOREHOLE SHOOTING (BCF)	839

STIMULATION TECHNOLOGY	CUMULATIVE RECOVERY (MMCF/WELL) 10 YRS	40 YRS
• BOREHOLE SHOOTING	116	386
• RADIAL STIMULATION		
-- rw-30'	176	536
-- rw-60'	230	650
• VERTICAL FRACTURE		
-- xf-150'	276	730
-- xf-600'	530	1,080

CUMULATIVE GAS RECOVERY

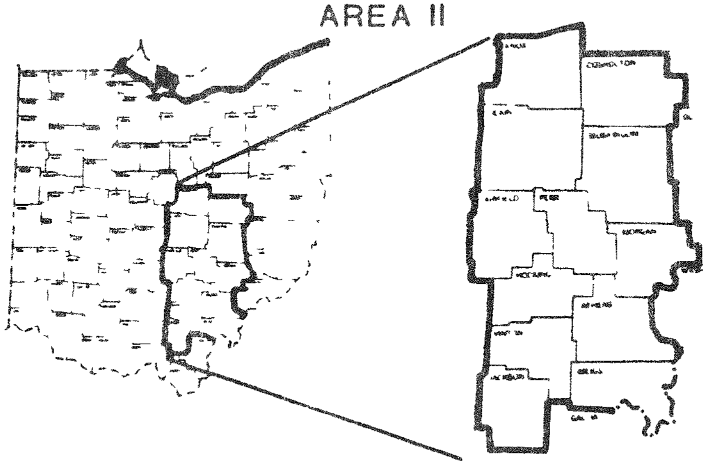


GAS PRODUCTION RATE



SUMMARY OF OHIO DEVONIAN SHALE GAS POTENTIAL

AREA II



BASIC DATA

KEY RESERVOIR PROPERTIES

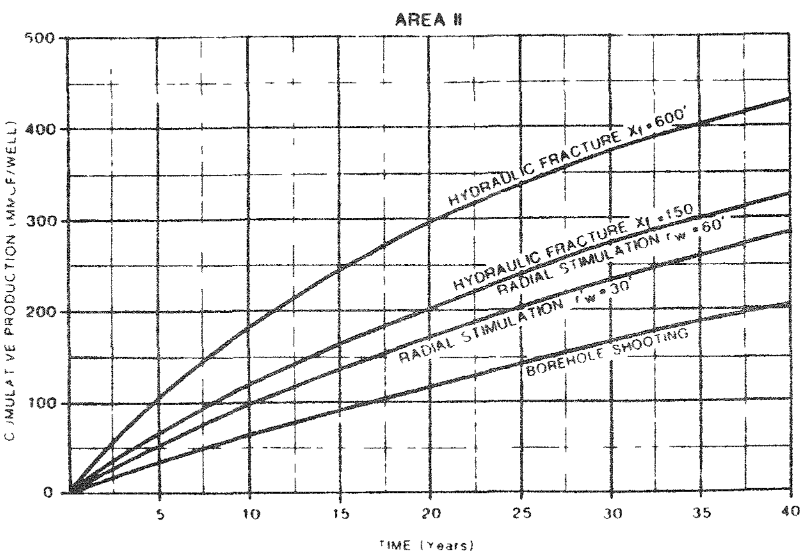
• DEPTH (ft)	1500
• ROCK PRESSURE (psig)	240
• GAS CONTENT (Mcf/Af)	90
• "NET" THICKNESS (ft)	60
• FRACTURE PERM (md)	2993
• INIT OPEN FLOW (Mcf/D)	25
• PERM ANISOTROPY (ratio)	6 1
• FRACTURE INTERSECTION ANGLE (°)	10
• FRACTURE SPACING (ft)	20

GAS POTENTIAL

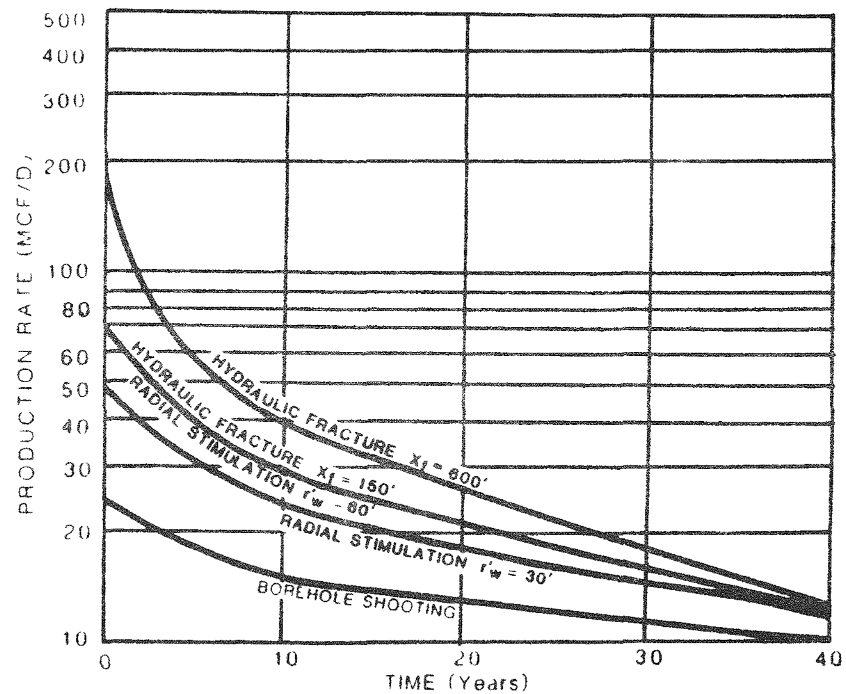
• DRILLABLE AREA (ACRES)	2,289,280
• RECOVERABLE GAS w/BOREHOLE SHOOTING (BCF)	2,947

STIMULATION TECHNOLOGY	CUMULATIVE RECOVERY (MMCF/WELL) 10 YRS	40 YRS
• BOREHOLE SHOOTING	64	206
• RADIAL STIMULATION		
-- rw-30'	98	284
-- rw-60	119	324
• VERTICAL FRACTURE		
-- xf-150'	121	327
-- xf-600'	190	434

CUMULATIVE GAS RECOVERY

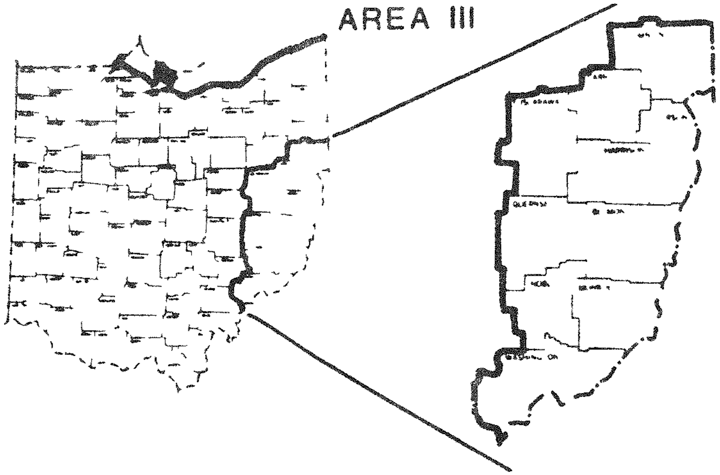


GAS PRODUCTION RATE



SUMMARY OF OHIO DEVONIAN SHALE GAS POTENTIAL

AREA III



BASIC DATA

KEY RESERVOIR PROPERTIES

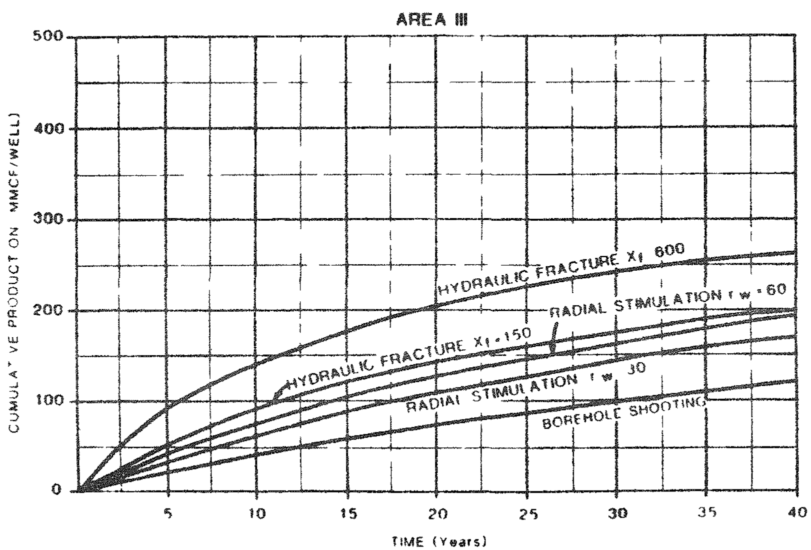
DEPTH (ft)	3560
ROCK PRESSURE (psig)	525
GAS CONTENT (Mcf/AF)	20
"NET" THICKNESS (ft)	120
FRACTURE PERM (md)	02
INIT OPEN FLOW (Mcf/D)	19
PERM ANISOTROPY (ratio)	4 1
FRACTURE INTERSECTION ANGLE (°)	20
FRACTURE SPACING (ft)	20

GAS POTENTIAL

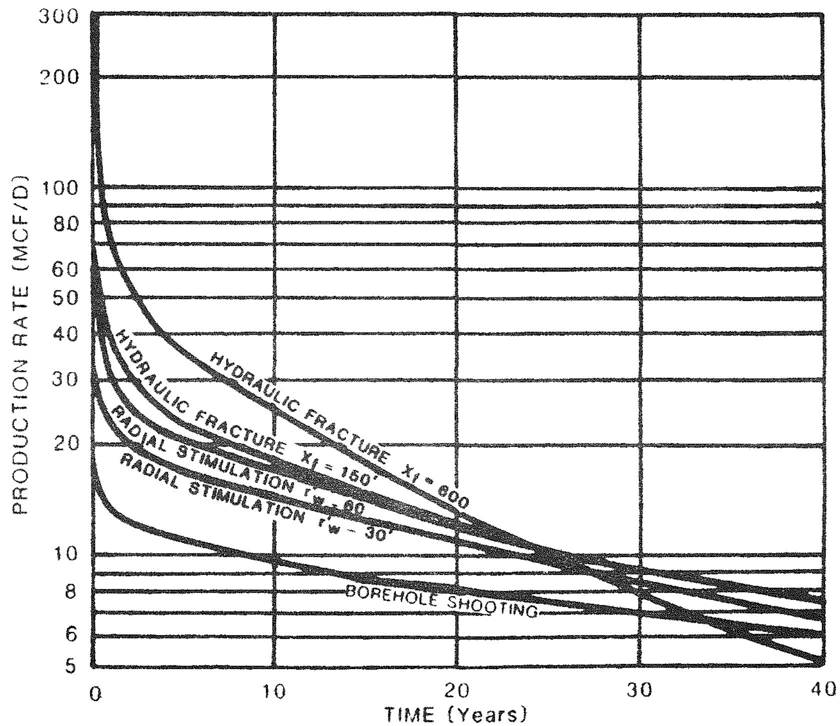
DRILLABLE AREA (ACRES)	1,836,000
RECOVERABLE GAS w/BOREHOLE SHOOTING (BCF)	1,459

STIMULATION TECHNOLOGY	CUMULATIVE RECOVERY (MMCF/WELL) 10 YRS	40 YRS
BOREHOLE SHOOTING	42	127
RADIAL STIMULATION		
- rw-30'	64	172
- rw-60'	79	196
VERTICAL FRACTURE		
-- xf-150'	85	203
-- xf-600'	142	265

CUMULATIVE GAS RECOVERY

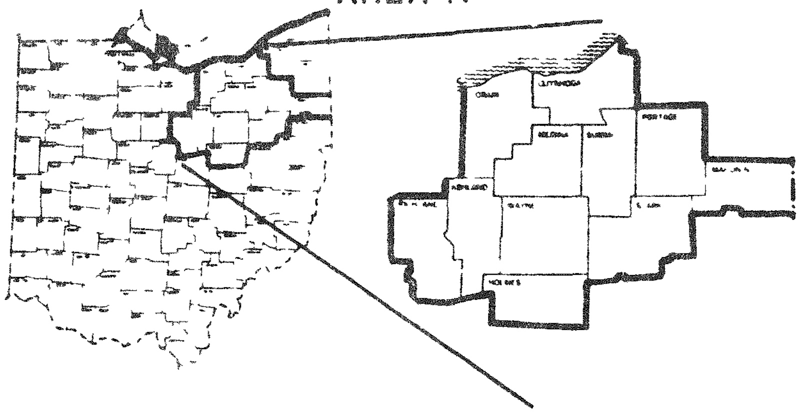


GAS PRODUCTION RATE



SUMMARY OF OHIO DEVONIAN SHALE GAS POTENTIAL

AREA IV



BASIC DATA

KEY RESERVOIR PROPERTIES

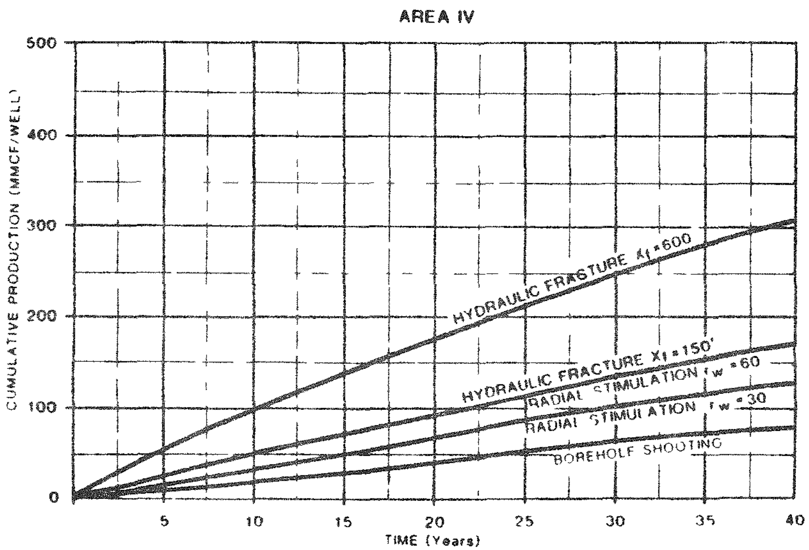
• DEPTH (ft)	1660
• ROCK PRESSURE (psig)	215
• GAS CONTENT (Mcf/AF)	140
• "NET" THICKNESS (ft)	105
• FRACTURE PERM (md)	0574
• INIT OPEN FLOW (Mcf/D)	8
• PERM ANISOTROPY (ratio)	8 1
• FRACTURE INTERSECTION ANGLE (°)	40
• FRACTURE SPACING (ft)	20

GAS POTENTIAL

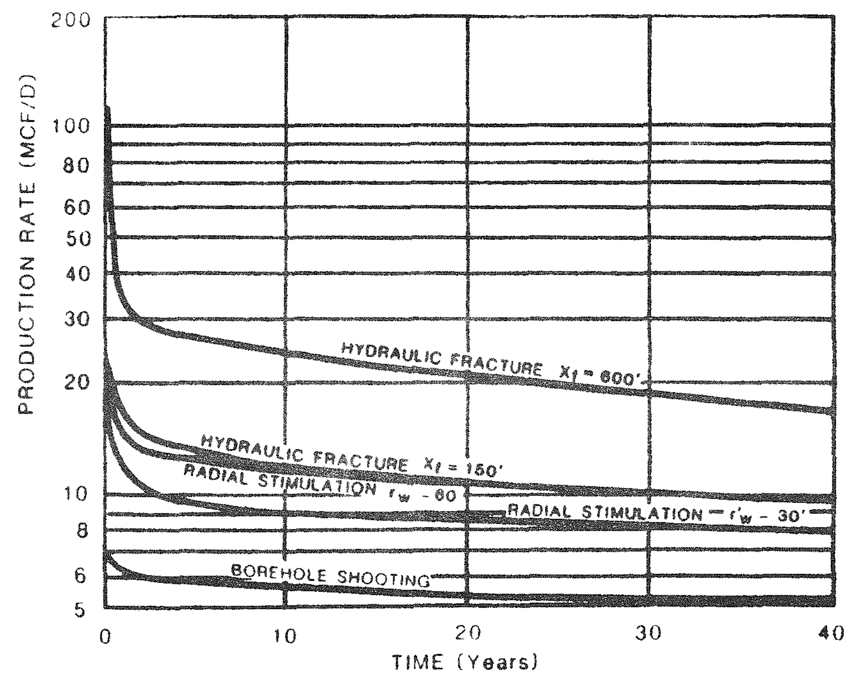
• DRILLABLE AREA (ACRES)	1,690,080
• RECOVERABLE GAS w/BOREHOLE SHOOTING (BCF)	836

STIMULATION TECHNOLOGY	CUMULATIVE RECOVERY (MMCF/WELL)	
	10 YRS	40 YRS
• BOREHOLE SHOOTING	21	79
• RADIAL STIMULATION		
-- rw-30'	36	128
-- rw-60'	47	164
• VERTICAL FRACTURE		
-- xf-150'	49	168
-- xf-600'	103	320

CUMULATIVE GAS RECOVERY

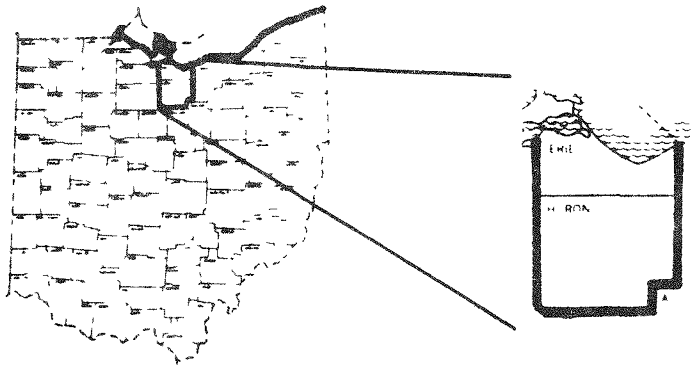


GAS PRODUCTION RATE



SUMMARY OF OHIO DEVONIAN SHALE GAS POTENTIAL

AREA V



BASIC DATA

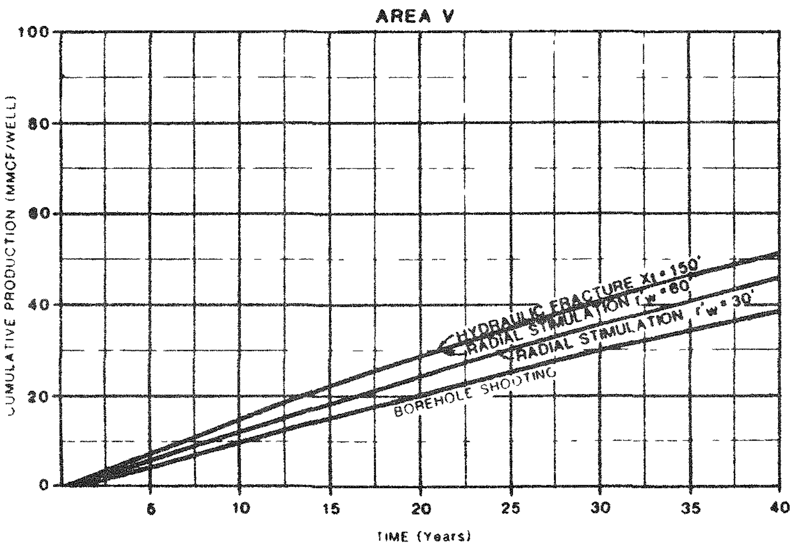
KEY RESERVOIR PROPERTIES	
• DEPTH (ft)	365
• ROCK PRESSURE (psig)	90
• GAS CONTENT (Mcf/AF)	200
• "NET" THICKNESS (ft)	10
• FRACTURE PERM (md)	4.429
• INIT OPEN FLOW (Mcf/D)	7
• PERM ANISOTROPY (ratio)	8 1
• FRACTURE INTERSECTION ANGLE (°)	40
• FRACTURE SPACING (ft)	20

GAS POTENTIAL

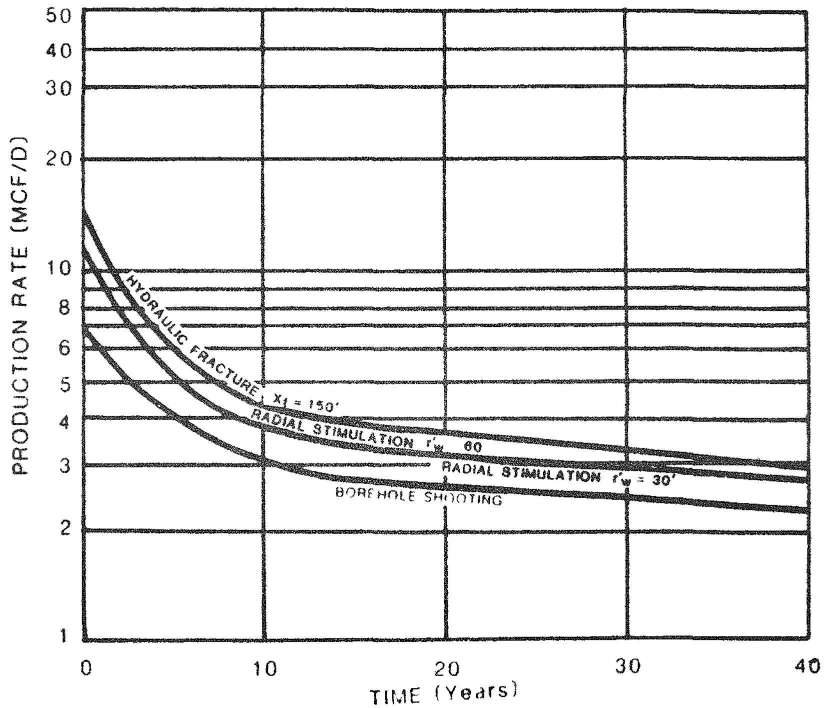
- DRILLABLE AREA (ACRES) 200,320
- RECOVERABLE GAS w/BOREHOLE SHOOTING (BCF) 49

STIMULATION TECHNOLOGY	CUMULATIVE RECOVERY (MMCF/WELL) 10 YRS	40 YRS
• BOREHOLE SHOOTING	11	39
• RADIAL STIMULATION		
-- rw-30'	14	47
-- rw-60'	15	51
• VERTICAL FRACTURE		
-- xf-150'	14	50

CUMULATIVE GAS RECOVERY

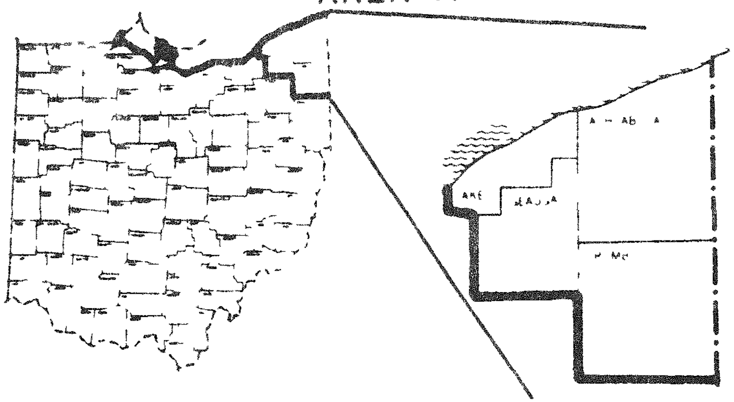


GAS PRODUCTION RATE



SUMMARY OF OHIO DEVONIAN SHALE GAS POTENTIAL

AREA VI



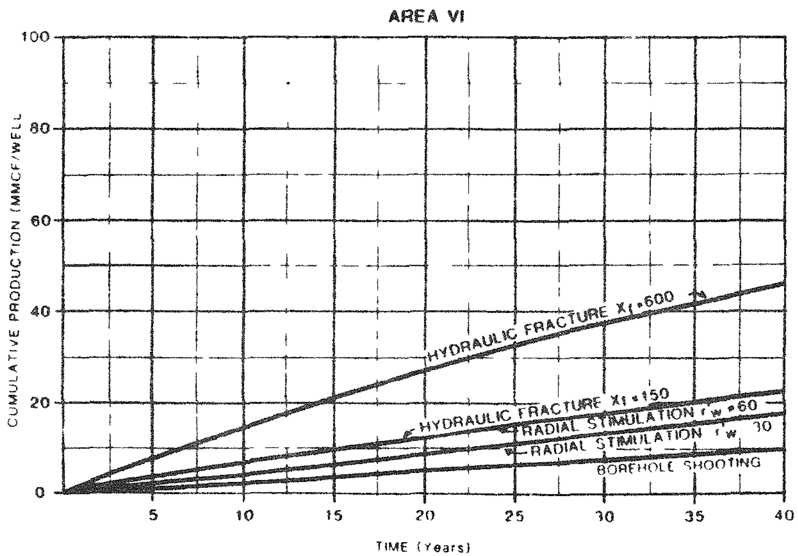
BASIC DATA

KEY RESERVOIR PROPERTIES	
• DEPTH (ft)	2,135
• ROCK PRESSURE (psig)	135
• GAS CONTENT (Mcf/AF)	50
• "NET" THICKNESS (ft)	100
• FRACTURE PERM (md)	02
• INIT OPEN FLOW (Mcf/D)	1
• PERM ANISOTROPY (ratio)	8 1
• FRACTURE INTERSECTION ANGLE (°)	40
• FRACTURE SPACING (ft)	20

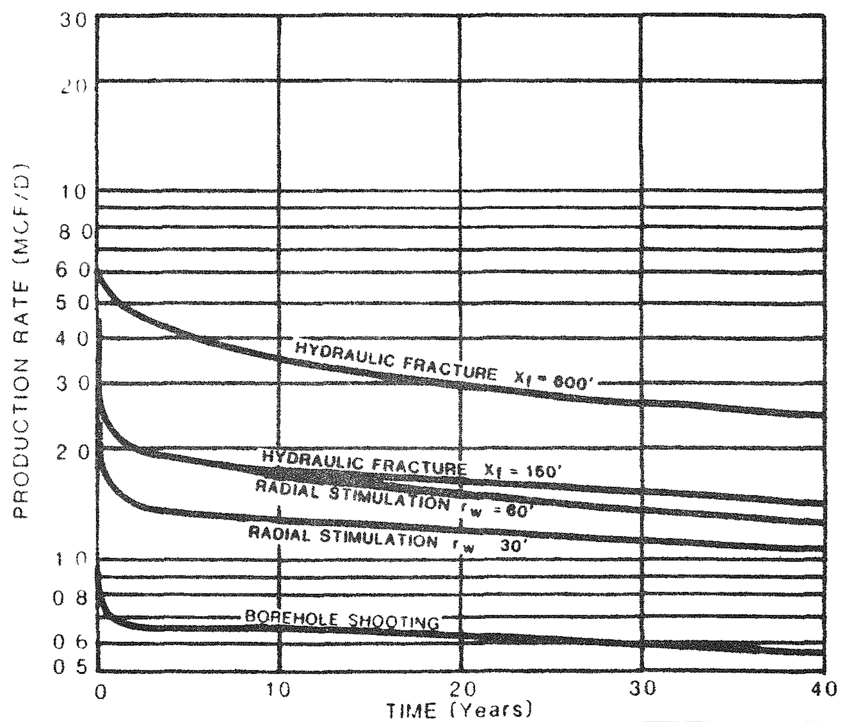
GAS POTENTIAL	
• DRILLABLE AREA (ACRES)	662,560
• RECOVERABLE GAS w/BOREHOLE SHOOTING (BCF)	41

STIMULATION TECHNOLOGY	CUMULATIVE RECOVERY (MMCF/WELL) 10 YRS	40 YRS
• BOREHOLE SHOOTING	3	10
• RADIAL STIMULATION		
-- rw-30	5	18
-- rw-60	7	24
• VERTICAL FRACTURE		
-- Xf-150	7	22
-- Xf-600'	15	47

CUMULATIVE GAS RECOVERY



GAS PRODUCTION RATE



I. HISTORICAL BACKGROUND

Devonian shales constitute one of the largest worldwide concentrations of organic carbon. Recent estimates of the total gas in-place range from 844 Tcf to 2,579 Tcf, as determined by the U.S. Geological Survey and Mound Facility, respectively. However, the resource potential and technological challenges of efficiently recovering and economically producing the hydrocarbons locked in the Devonian shales are formidable and have yet to be solved.

The geologic setting of the Devonian shales is highly complex. The shales are a combination of source bed, reservoir, and seal in multiple stratigraphic horizons. Gas production is dominated by natural fractures and other permeability channels. The resource includes free gas in the natural fracture system and in the rock matrix, plus adsorbed gas on the surfaces of the organic kerogen. Of these three sources, adsorbed gas accounts for the largest share, approximately 85% of the total gas in-place.

To date, full development of this resource has been impeded by a lack of scientific description and analysis of the gas production mechanisms in the organic shales. Conventional geological and engineering measures of the drainage area, net productive interval, permeability, and porosity need to be supplemented by improved geological models of the natural fracture system, permeability anisotropy, and the release of adsorbed gas.

In addition, efficient development has been constrained by limitations in extraction and well stimulation technologies and limited understanding of how stimulation technologies perform in the naturally fractured, anisotropic shale rocks.

Recently, a number of major studies and activities have been completed under the Eastern Gas Shales Project (EGSP) that provide a basis for advancing the understanding of the Devonian gas shales. Under the sponsorship of the U.S. Department of Energy's Morgantown Energy Technology Center (DOE/METC), two geological and geochemical assessments of the Devonian shales have been completed by the Mound Facility and Cliffs Minerals, namely:

- "Resource and Exploration Assessment of the Oil and Gas Potential in the Devonian Gas Shales of the Appalachian Basin," 1982, Mound Facility.[1]

- "Basin Analysis of the Devonian Shales in the Appalachian Basin," June 1982, Cliffs Minerals.[2]

Their detailed reports provide much information as to the fracture system, stratigraphic sequence and gas content of the shale. In addition, DOE/METC has developed a reservoir simulator called SUGAR (Simulator for Unconventional Gas Resources) that is capable of handling many of the unique features of the shale not commonly found in other simulators, such as dual porosity, fracture flow, and permeability anisotropy.[3]

Paralleling the analytic work has been a series of field research projects, such as the Offset Well Test Program (OWTP)[4,5] in Miegs County, Ohio to identify the net productive interval and permeability anisotropy; the drilling of a deviated well to measure natural fracture spacing; and, the drilling of a series of Eastern Gas Shales Program (EGSP) core wells to establish basic data on shale porosity, permeability, and organic carbon content.

Finally, there has been a recent upsurge in drilling, testing, and well stimulation by industry that is yielding new data on previously undrilled areas of the Appalachian Basin.

II. STUDY PURPOSE, APPROACH, AND METHODOLOGY

A. KEY TECHNICAL QUESTIONS

Building on the accomplishments of the previous research, it becomes appropriate to examine the remaining key technical questions in order to determine the gas reserves, such as:

- How to properly characterize and interpret the gas production mechanism;
- How to select the productive interval consistently in areas of favorable gas potential;
- What types of well stimulation techniques to use or develop further with additional research; and
- How to reliably estimate gas flow rates and ultimate recovery.

B. STUDY PURPOSE

The current study begins to address these questions by integrating the previous research work and collecting additional data toward the following five study objectives:

1) A rigorous investigation, model development, and description of the gas production mechanisms in the Devonian gas shales. This study examines the gas storage and production mechanisms in the naturally fractured, dual porosity systems that govern productivity in Devonian shales beyond the conventional mechanisms of drainage area, net pay, porosity, permeability, and pressure.

2) The collection and assembly of essential geologic and reservoir data. While much of the data required for this analysis is assembled from previous research, it is augmented by the collection of new data on well completion and gas production.

3) The partitioning of the state into study regions. For the purposes of analysis, the state of Ohio is partitioned into regions based on geologic data and gas production trends.

4) An investigation of the efficiency of alternative well stimulation and production strategies. The relative efficiencies of borehole shooting, radial stimulation, and vertical fracturing are analyzed using a numerical reservoir simulator specifically designed for the key production features of the Devonian shales.

5) An estimate of the technically recoverable reserves in Ohio. Technically recoverable reserve estimates are made for each of the major partitioned areas of Ohio, for various stimulation techniques; the target interval of this analysis will be the Middle and Lower Huron shale members of the Upper Devonian Ohio Shale.

This report builds and improves on the technologic knowledge base to provide a scientific understanding of the Devonian Shales Gas resource. It's primary audience is intended to be a explorationists, geologists, and R&D Managers interested in a detailed basin level analysis of the resource along with independent operators interested in choosing a stimulation technique in a given area. The purpose of this study is to examine these issues in a regional setting. Therefore, the findings of this study are not intended to be representative of any specific lease or well location in the state.

C. GENERAL APPROACH

The general approach used by this study is to build on the existing knowledge gained in the last six years from the DOE Eastern Gas Shales Program (EGSP), and in particular from the several important pieces of work recently concluded under the sponsorship of DOE/METC. The Mound report, Cliffs Minerals studies, and the results and analyses of the Offset Well Test Program are used as primary sources of geologic data for this study. In addition, gas production and open flow data generated from the recent upsurge of drilling in the Appalachian Basin are used to supplement the primary sources.

These data are used to develop a representative data set for each county in Ohio for the target interval. Several reservoir parameters do not vary widely and are kept constant over the study area. Other reservoir parameters that show regional variations are individually calculated for each county using actual data or extrapolation from neighboring counties. Isoline maps are developed for these data using information from the known counties with documented data as control points.

The SUGAR simulator is used to match production data and back-calculate the remaining unknown reservoir parameters. It is also used to validate the other reservoir parameters using a history matching approach, comparing the simulated production and historical production records. In this manner the geologic/reservoir data are developed; furthermore, the data sets are comparable.

Base case gas production forecasts are made for each county using the SUGAR simulator and the data developed. Ohio is then partitioned into "comparable" areas based on 40-year cumulative production, joint-stress relationships, tectonophysics, and the mechanical fabric of the shales. The effect of improved well stimulation, due to vertical fracturing and radial stimulation, are modeled for each of the partitioned areas to analyze the relative efficiencies of each method. Finally, a series of additional analyses are performed to better assess the importance of the key assumptions used in this study and to take into account other factors affecting production.

D. METHODOLOGY

The methodology closely followed the general approach and consisted of eight major steps, as discussed below:

1) Identification of Constant Geologic/Reservoir Data. Several reservoir parameters, such as matrix permeability and porosity, were found not to vary widely and thus were kept constant over the study area. These reservoir data and parameters were assembled from:

- Historical gas production and well records,
- The EGSP core well program, and
- The Offset Well Test Program (Meigs County, Ohio)

2) Development of Variable Geologic Data By County. Reservoir parameters that showed strong regional variation, such as gas content and pressure, were developed for each county from actual data or were extrapolated from a series of isoline maps developed for Ohio. These data were based on:

- Geological and geochemical reports by Cliffs Minerals and Mound Facility;
- Fracture conductivity studies by Terra Tek;[6]
- Stress-ratio maps prepared by METC/DOE;[7] and
- Rock pressure data from 257 wells in 15 counties.

3) Assembly of Actual Gas Production Data. Historical gas production data for Ohio were gathered from state and company records, as follows:

- Long-term production data were assembled from 108 wells in 11 counties; and

- Initial open flow (24 hr.) data were collected from 222 wells in 15 counties.

4) History Matching of Production Data and Productive Interval. A reservoir simulator entitled Simulator for Unconventional Gas Recovery (SUGAR) was used to match production data and back-calculate the remaining unknown reservoir parameters of fracture permeability and net productive interval, as well as to ensure consistency in the basic data.

5) Definition of the Fracture Regimes. Beyond the data required for analyzing the performance of well stimulation by borehole shooting, additional geological data were required to properly evaluate well performance with improved stimulation technology. This additional data included:

- Determining directional components of fracture permeability to reflect permeability anisotropy;

- Identifying the expected angle of intersection between induced and natural fractures to estimate whether the induced fracture will cross or terminate in the natural fracture system;[8] and

- Establishing an optimum well drainage geometry to best match permeability anisotropy and stimulation method.

6) Development of Six Regional Partitions for Ohio. Gas production estimates were made for each county using the geologic and production data developed in Steps 2 through 5, above. The state of Ohio was then partitioned into six areas based on 40-year cumulative gas production, and the key geological data that establish the natural stress and native fracture distribution.

7) Development of Representative Data by Partitioned Area. The essential geologic data were aggregated and compiled by each of the six partitioned areas.

8) Delineation of Alternative Stimulation Cases. Four well stimulation techniques, beyond traditional borehole shooting, were evaluated:

- Small Radial Stimulation (r'_w = 30 feet): attainable with emerging technological improvements in omni-directional stimulation;

- Large Radial Stimulation (r'_w = 60 feet): potentially attainable with major improvements in explosive and propellant technology;

- Small Vertical Fracture (x_f = 150 feet): attainable, but not yet fully controllable or predictable with current technology; and

- Large Vertical Fracture (x_f = 600 feet): potentially attainable with significant advances in technology or alternate fracture fluids and proppants.

At the conclusion of these steps, the data which had been assembled by area was analyzed for each of the delineated stimulation cases using the SUGAR Model.

III. COLLECTION AND ASSEMBLY OF DATA

This chapter details the collection of the essential geologic and reservoir data on the Devonian shales of the Appalachian Basin, the assembly of representative data for Ohio by county, and the use of the data to estimate technically recoverable reserves of Devonian shale gas in Ohio.

A. IDENTIFICATION OF GEOLOGIC/RESERVOIR DATA

The required geologic/reservoir parameters and their sources are discussed below:

1. Parameters Required

History matching of long-term production data revealed that the following parameters are required to properly characterize the productive mechanism for Devonian shales:

- Drainage Area (A); acres
- Matrix Permeability (k_m); md
- Matrix Porosity (Φ_m); percent
- Fracture Porosity (Φ_f); percent
- Gas Content (G_c); scf/cf
- Rock Pressure (P_i); psia
- Line Pressure (P_l); psia
- Fracture Spacing (a); feet
- Natural Fracture Permeability (k_f); md
- Productive Thickness (h); feet

In addition, to calibrate the model, initial open flow and cumulative gas production data were required.

2. Sources of Data

The major sources of data used in this study were:

- Historical gas production records
- Offset Well Test Program
- Mound report
- Cliffs report

These sources are discussed in further detail below:

a. Historical Production Records--Production and Reservoir Data. A large number of well records were obtained from the Ohio Geological Survey and gas production companies. Approximately 900 records of wells that penetrated or were completed in the Devonian shale, spanning the time period from 1898 to 1981, were screened for usable rock pressure and initial open flow data. Of these, approximately 300 wells in 22 countries contained usable data for the study.

Initial production data were acquired for 15 counties, as shown below:

County	Number of Wells With Open Flow Production Data
Athens	5
Ashtabula	4
Belmont	2
Carroll	2
Columbiana	1
Gallia	7
Knox	3
Lawrence	30
Licking	26
Lorain	5
Meigs	19
Monroe	18
Noble	22
Trumbull	11
Washington	67
TOTAL	222

The locations of the wells that provided initial and long-term gas production data are shown on Exhibit 3. A detailed description of data sources and location is provided in Appendix A.

The bulk of the long-term production data, consisting of 108 wells in 11 counties, were obtained from proprietary company sources and data supplied by DOE/METC. The data included wells with initial flow commencing as early as 1922 and as late as 1976. The county-by-county tabulation of the long-term gas production data is provided below:

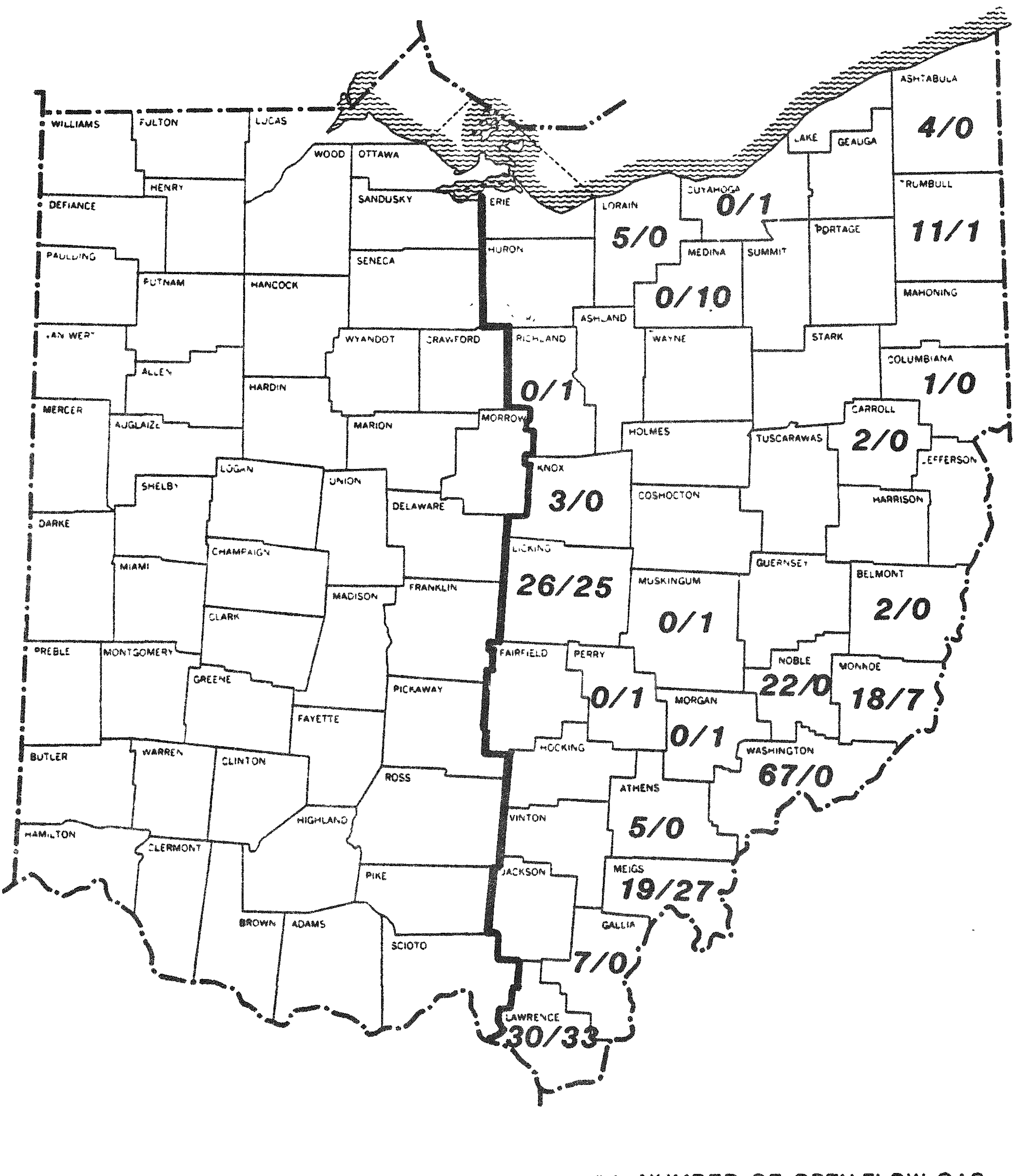
County	Number of Wells With Long-Term Production Data
Cuyahoga	1
Lawrence	33
Licking	27
Meigs	25
Medina	10
Monroe	7
Morgan	1
Muskingum	1
Perry	1
Richland	1
Trumbull	1
TOTAL	108

Although earlier studies indicated the availability of larger quantities of data, the records above represent the latest data set as compiled by the Ohio Geological Survey. Many wells which were not truly producing from the shale have been deleted.

b. Offset Well Test Program--Fracture and Rock Matrix Properties. An extensive well test program (OWTP) was conducted in Meigs County, Ohio, during 1980 and 1981. The test included drawdown and buildup interference testing between a borehole shot producing well and two offset wells. The base well was originally stimulated by borehole shooting and has a long-term production history. The two offset wells were drilled at approximately 90 degree angles relative to the producing well.

Exhibit 3

AVAILABILITY OF PRODUCTION DATA BY COUNTY



#/ NUMBER OF OPEN-FLOW GAS PRODUCTION RECORDS

/# NUMBER OF LONG-TERM GAS PRODUCTION RECORDS

The first offset well (OH-9) was cored from about 2,923 feet to near the base of the Huron shale at 3,373 feet. Porosity and permeability measurements on selected core samples were made by Core Laboratories in Dallas, Texas and Monsanto Research Corporation's Mound Facility in Miamisburg, Ohio.

In addition, the OWTP site served as a control and calibration point for calculations of permeability anisotropy, fracture permeability, and fracture spacing for the state.

c. Mound Report--Geochemical Data. The recently completed report, Resource and Exploration of the Devonian Gas Shales by Mound, provided the necessary information on free and sorbed gas content. The major aspects of this study are summarized below:

- Detailed physiochemical analysis was performed on over 2,000 samples from EGSP core wells; samples were selected at 10 to 20-foot intervals in each of the EGSP core wells.

- A controlled-offgassing procedure was developed and validated via comparison with pressure core barrel measurements.

- The shale interval (Upper Devonian age rock) was subdivided into 17 stratigraphic units, as identified in Table 1.

- Algorithms were developed for calculating indigenous gas in-place, based on organic carbon content, thermal alteration index (TAI) and organic matter origin.

The locations and a detailed description of the EGSP core wells used in the Mound and Cliffs studies may be found in Appendix B.

d. Cliffs Report--Geologic Data. The majority of the geologic data were obtained from the report, Basin Analysis of the Devonian Shales in the Appalachian Basin by Cliffs Minerals.

Table 1

STRATIGRAPHIC DEVONIAN SHALE UNITS

SYSTEM	SERIES	STAGE	STRATI-GRAPHIC UNIT	PHASE/UNIT
DEVONIAN	Upper	Ohio Shale	17	Cleveland
			16	Chagrin
			15	Late Upper Huron
			14	Early Upper Huron
			13	Late Middle Huron
			12	Early Middle Huron
			11	Late Lower Huron/Late Dunkirk
			10	Early Lower Huron/Early Dunkirk
	Middle	Olentangy Shale	9	Upper Olentangy/Java FM./Hanover
			8	Middle Olentangy/Angola Shale
			7	Late Lower Olentangy/Late Rhinestreet
			6	Early Lower Olentangy/Late Rhinestreet
	Lower	Genesee	5	Sonyea/Middlesex
			4	Genesee/Geneseo
		Hamilton	3	Hamilton Group/Post-Marcellus
		Marcellus	2	Late Marcellus
			1	Early Marcellus

In September 1980, Cliffs Minerals, Inc., a division of the Cleveland-Cliffs Iron Company, launched a major integration program to analyze geologic and engineering data that were accumulated by many contractors under the Eastern Gas Shales Project. The purpose was to identify areas with good hydrocarbon potential and delineate structural features. As part of this, a series of activities were undertaken by Cliffs to define and give values to the geologic parameters affecting gas production from Devonian shales. These activities included:

- Regional fracture (joint) studies,
- Stress analysis of the basin,
- Physical characterization of the shales,
- Definition of geologic structural features, and
- Lithologic and geochemical descriptions.

The Cliffs study was primarily used in this study to estimate permeability anisotropy, major and minor natural fracture orientation, and preferred orientation of induced fractures.

B. DEVELOPMENT OF REPRESENTATIVE DATA BY COUNTY

Geologic and reservoir data were divided into two categories in this study: (1) constant reservoir characteristics, and (2) variable reservoir characteristics. Those reservoir properties that were found not to vary widely across the state were fixed at constant values based on standard production practices and EGSP core well data. For reservoir properties that were found to vary across the state, data were collected on a county basis and extrapolated into counties where data were unobtainable.

1. Constant Reservoir Characteristics

a. Drainage Area. The traditional field development practice is to use a well spacing of 150 to 160 acres. The majority of the well records surveyed in this study indicated a well spacing of 160 acres, which became the Base Case drainage area used in this study. The spacing was also chosen for analytical purposes in other reports, such as the NPC Devonian Shale report (Unconventional Gas Sources - Vol. III Devonian Shales, 1980). However, current practice is to drill on a closer spacing. To take this into consideration, the results of drilling on 80-acre spacing are examined in Chapter VII: Other Factors Affecting Production.

b. Target Interval. The productive interval analyzed in this study is composed of the Middle and Lower Huron units of the Ohio shale. Over 95 percent of the Devonian shale wells examined in this study were producing from this interval. This interval was also identified as the gas source in the Offset Well Test Project. The remaining wells were producing from the Cleveland and Chagrin units and had low gas production dedicated to domestic rather than commercial use.

c. Matrix Properties. Although a certain amount of variation in matrix properties was found, it was decided to use nominal values of 1% for shale matrix porosity and 5 x 10^{-6} md for matrix permeability. These values are based on measurements from the Offset Well Test Program and supported by values from the other Ohio EGSP core wells. A summary of the measurements made in support of the OWTP and the measurements from the Ohio EGSP core wells are presented in Table 2.

d. Fracture Porosity. The porosity of the natural fracture system within the Devonian shales was determined quantitatively in Meigs County, Ohio as part of the Offset Well Test Program. From analysis of drawdown, build up, and interference tests, a nominal value of 0.09% was calculated, and values in the range of 0.01% to 0.5% were believed to be reasonable. However, for lack of other data and because long-term production in the shale is essentially independent of fracture porosity, the value of 0.09% was used as a constant throughout the study.

Table 2

SUMMARY OF SHALE MATRIX PARAMETERS FROM OHIO EGSP CORE WELLS+

County	Well/Sample	Depth (ft)	Permeability (md)	Porosity (%)	Gas Content (Scf/cu ft)	Gas Content (Mcf/Ac-ft)
Carroll	OH-1	2,112 - 2,117	-	.6 to 3.1	-	-
		2,135 - 3,189	-	.4 to 1.1	-	-
Washington	OH-2	3,510 - 3,636	-	.9 to 3.8	-	-
Knox	OH-3/23	1,031	1.3×10^{-5}	-	-	-
	OH-3/24	1,052	10^{-9}	-	-	-
	OH-3/25	1,074	1.8×10^{-4}	-	-	-
	OH-3/27	1,131	7.5×10^{-5}	-	-	-
Ashtabula	OH-4/7	549	2.0×10^{-3}	-	-	-
	OH-4/39	748	10^{-9}	-	-	-
	OH-4/199	1,351	10^{-9}	-	-	-
	OH-4/202	1,361	5.1×10^{-6}	-	-	-
Lorain	OH-5	---No Information---				
Gallia	OH-6-1*	2,318 - 2,563	-	-	.438	19.1
	OH-6-2*	2,260 - 2,498	-	-	.666	29.0
	OH-6-3*	2,546 - 2,791	-	-	.450	19.6
	OH-6-4*	2,543 - 2,790	-	-	.833	36.3
	OH-6-5*	2,206 - 2,446	-	-	1.49	65.0
Trumbull	OH-7	---No Information---				
Noble	OH-8	---No Information---				
Meigs	OH-9/16	3,076	6.3×10^{-6}	-	.425	18.5
	OH-9/17	3,089	6.3×10^{-6}	-	-	-
	OH-9/27	3,181	6.7×10^{-5}	-	1.19	169.
	OH-9/30	3,214	6.7×10^{-5}	-	-	-
	OH-9/42**	3,340	-	1.08	.889	38.7
	OH-9/43**	3,343	-	-	1.05	45.7
	OH-9/70A++	3,352 - 3,353	< 0.00001	0.9	-	-
	OH-9/70B++	3,352 - 3,353	< 0.00001	1.0	-	-
	OH-9/71B++	3,355 - 3,355	< 0.00001	1.0	-	-
	OH-9/71A++	3,355 - 3,355	< 0.00001	1.1	-	-
	OH-9/72A++	3,367 - 3,367	< 0.00001	1.0	-	-
	OH-9/72B++	3,367 - 3,367	< 0.00001	0.9	-	-

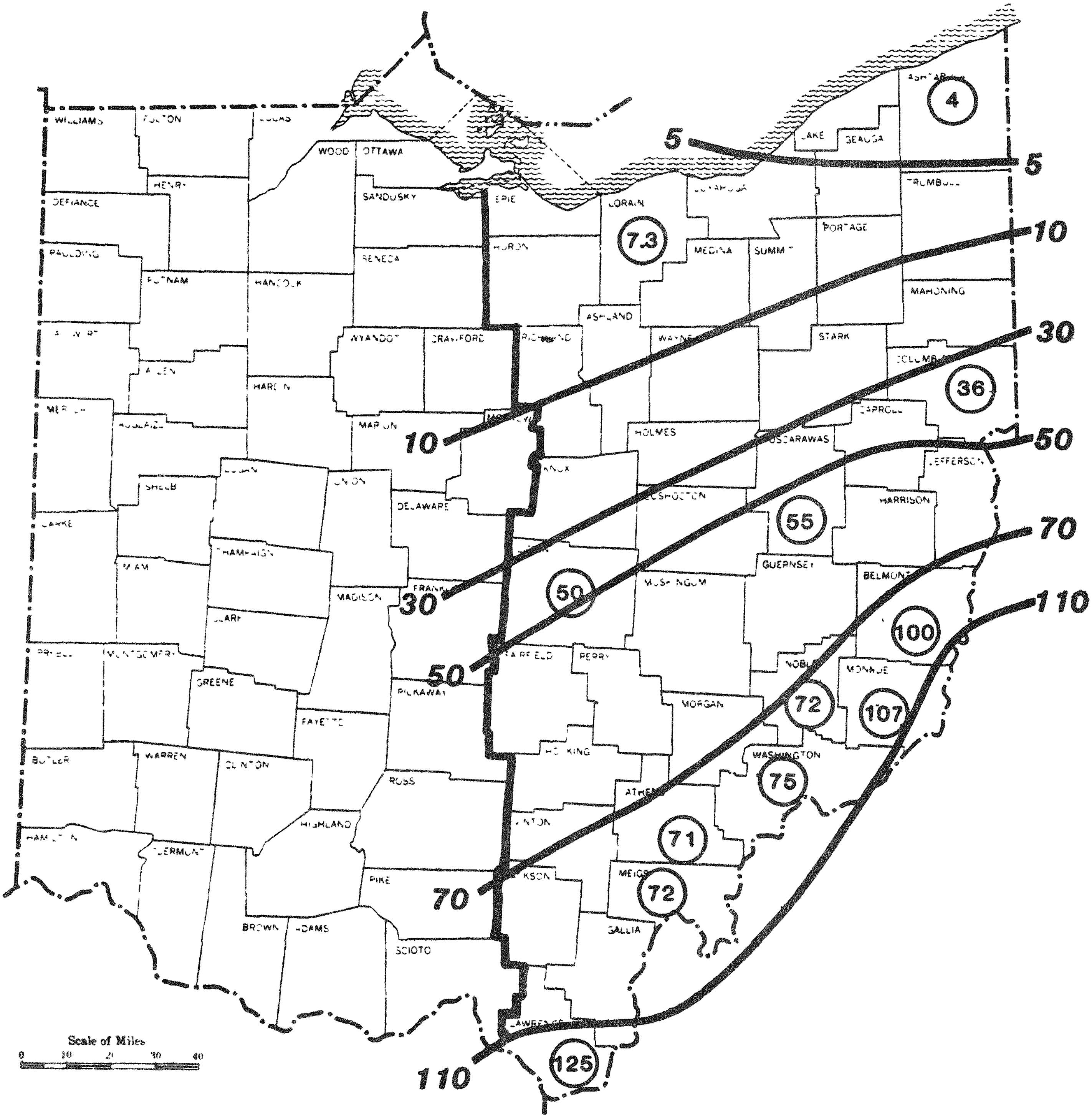
\+ Taken from Mound Lab compiled physical and chemical characterization of Devonian gas shale core wells.

++ Taken from Special Core Analysis Study on Offset Well No. 10056A (Meigs Co., Ohio) performed by Core Laboratories, Inc. for SAI.

* Only Lower Huron member included.

** Samples in known productive zone (from OWTP) included.

Exhibit 4
INITIAL OPEN FLOW
(Mcf/24 Hours)



2. Variable Reservoir Characteristics

a. Initial Open Flow. Company well records and Ohio Geological Survey well cards were reviewed and analyzed to determine the initial open flow rates. Data were available and validated for 12 counties. These records included data from both borehole shooting and fracturing. For those wells which were fractured, a productivity index ratio of 5 was utilized to convert initial flow to a borehole shot baseline level. While there is a considerable amount of error and variance in open flow data, the data were screened to eliminate any obvious outliers and anomalies. Data within a county was averaged for the productive shale interval. The average values within a county produce a definite trend across the state. The resulting intial open flow isolines are shown on Exhibit 4.

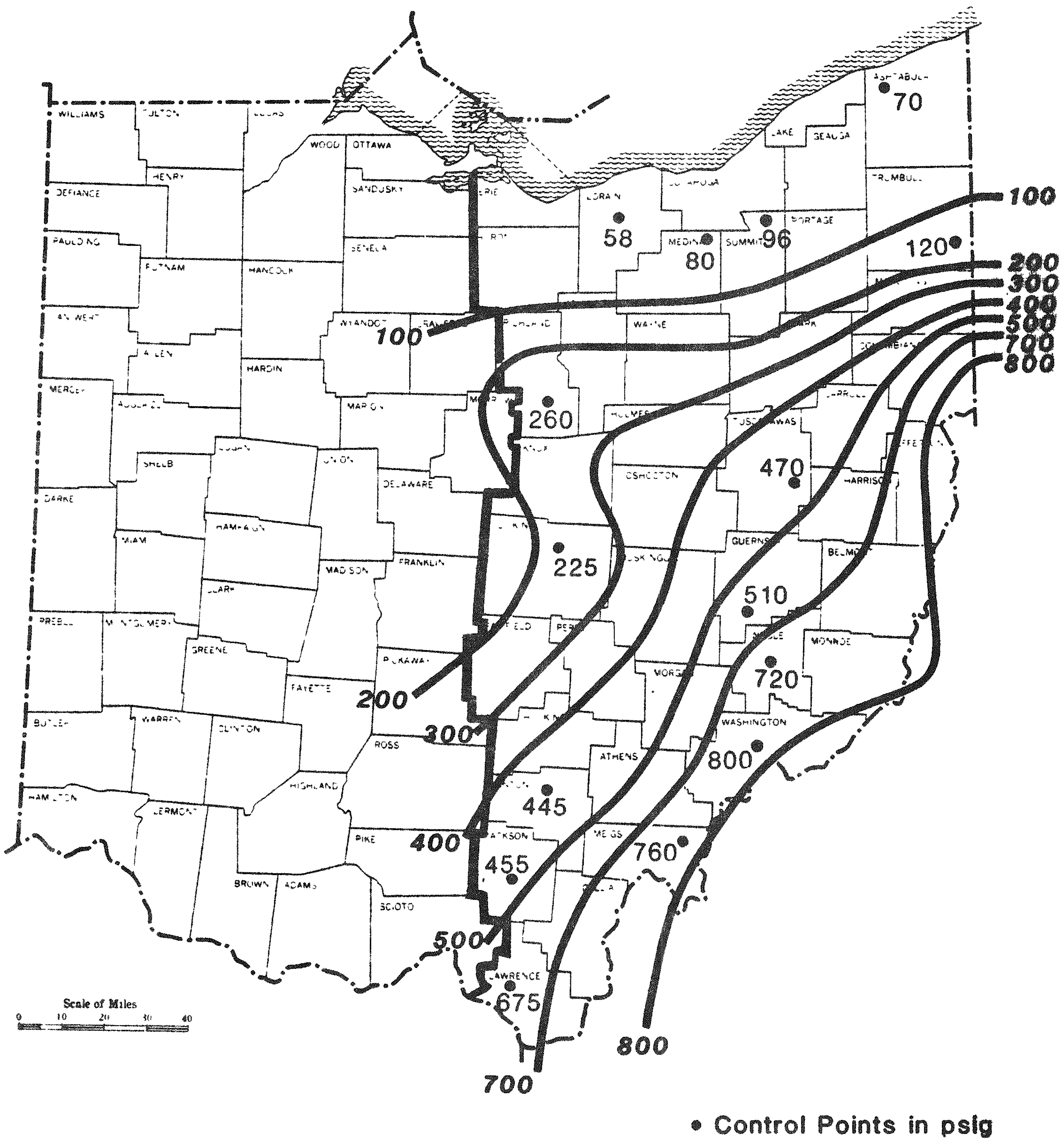
b. Rock and Line Pressure. Initial rock pressure data were collected for 15 counties, from company well records and Ohio Geological Survey well cards. The data for each county were then averaged and used as control points in plotting a pressure isoline map, Exhibit 5. The line pressure was based on the initial rock pressure, as shown on the following table:

Rock Pressure (psia)	Line Pressure (psia)
Less than 100	25
100 - 300	50
Greater than 300	100

c. Gas Content. Basin gas content contour maps prepared by Mound for the Appalachian Basin were used to establish the starting point for estimates of the volume of "sorbed and free" gas for each of the 17 stratigraphic intervals identified. These maps included the thickness, organic carbon content, and thermal alteration index for each of the 17 stratigraphic units.

Exhibit 5

ROCK PRESSURE (psig)



• Control Points in psig

Exhibit 6 from the Mound report is representative of the gas content for one of the stratigraphic units, the Late Lower Huron member.

To obtain gas content data by county for use in the SUGAR simulator, the Mound contour maps were used to establish representative gas content values for each county. This refinement was done for each of the 17 stratigraphic units, including the three units in the Lower and Middle Huron members selected as the target intervals in this study.

Exhibit 7 shows an isoline map of gas content compiled by this study from the Mound maps for the Middle and Lower Huron units. This map was used together with shale matrix porosities to calculate the "free" and "sorbed gas content" for use in the simulator.

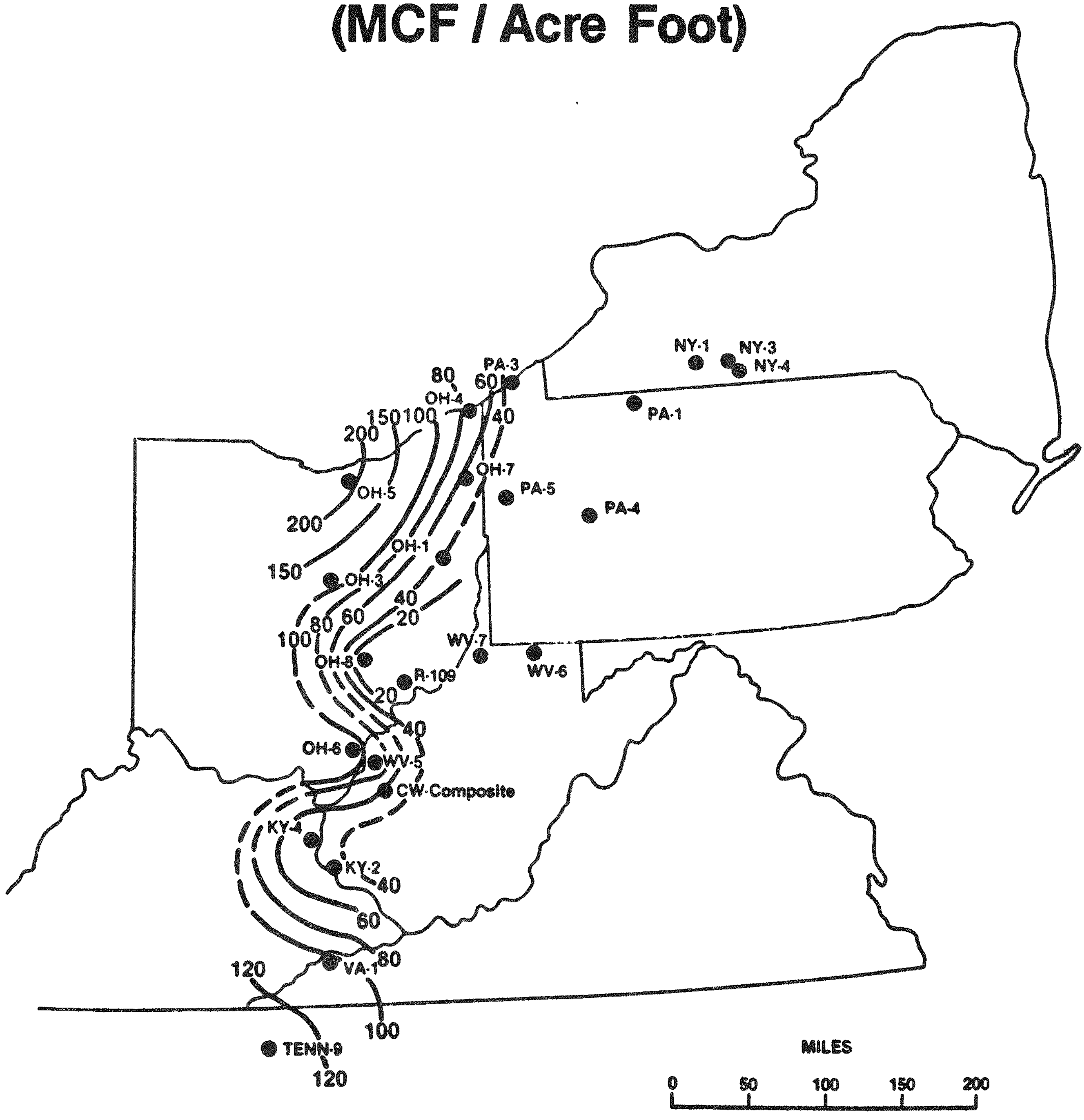
d. Fracture Spacing. The natural fracture spacing was determined by examining the number of joints per foot of shale interval, based on data in the Cliffs study. The close match between the Cliffs data and the fracture spacing established by the DOE/METC drilled deviated well (in Meigs County) gave confidence to this analytic approach for establishing fracture spacing. Spacing and direction of the micro-fault systems were also identified for Ohio from the Cliffs data and are discussed later under fracture orientation.

The relative orientation of the natural fractures and the induced fractures is important, since they combine to provide the permeability conduit from which the sorbed and matrix gas will be produced. Cliffs placed major emphasis for their fracture directions on the induced fractures and prepared a series of maps and tables identifying the fracture directions in an attempt to indicate how production would be enhanced as a function of fracture orientation.

The core samples from the Cliffs report give an accurate estimate of fracture spacing only for the area immediately around the core site.

Exhibit 6

CALCULATED INDIGENOUS GAS CONTENT (MCF / Acre Foot)

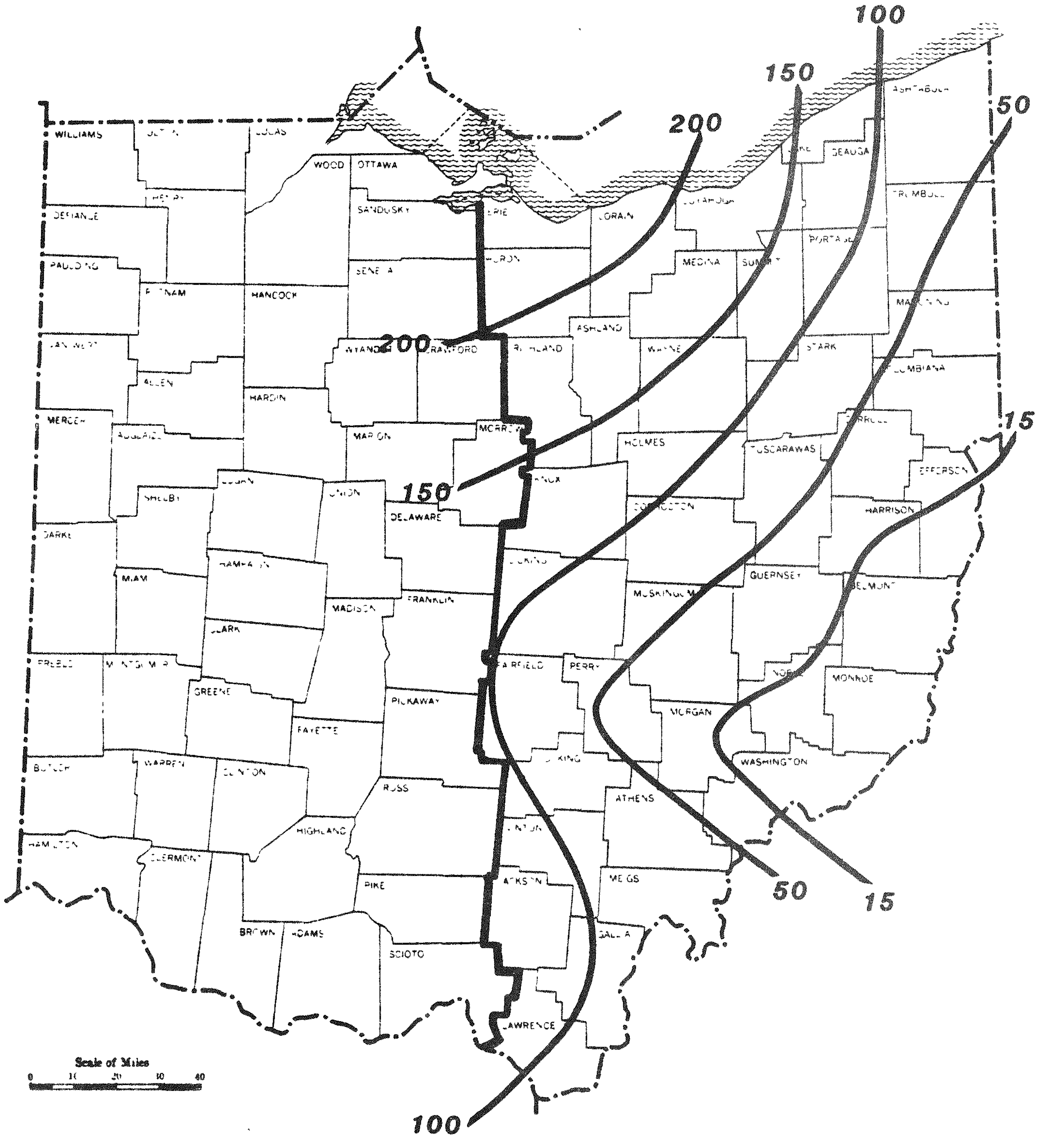


LATE LOWER HURON/LATE DUNKIRK TIME

Map Unit 11

Exhibit 7

LOWER AND MIDDLE HURON UNITS
Gas Content (Mcf/AC-Ft.)



spacing in conjunction with the fracture data from the EGSP core wells. The fracture spacing is shown in Exhibit 8.

e. Fracture Permeability. Natural fracture permeability was estimated for each county in Ohio using analysis developed by Terra Tek and presented by Horton.[9]

Assuming parallel natural fractures and accepting that some adjustment between laboratory and field results might be necessary, the following relationship was used for the determination of bulk natural fracture system permeability.

$$k_f = \frac{(k_f' \cdot w_f)\,C}{S}$$

Where:

k_f' = intrinsic fracture permeability, md
w_f = fracture width, cm
S = fracture spacing, cm
k_f = bulk fracture system permeability, md
C = calibration constant, dimensionless

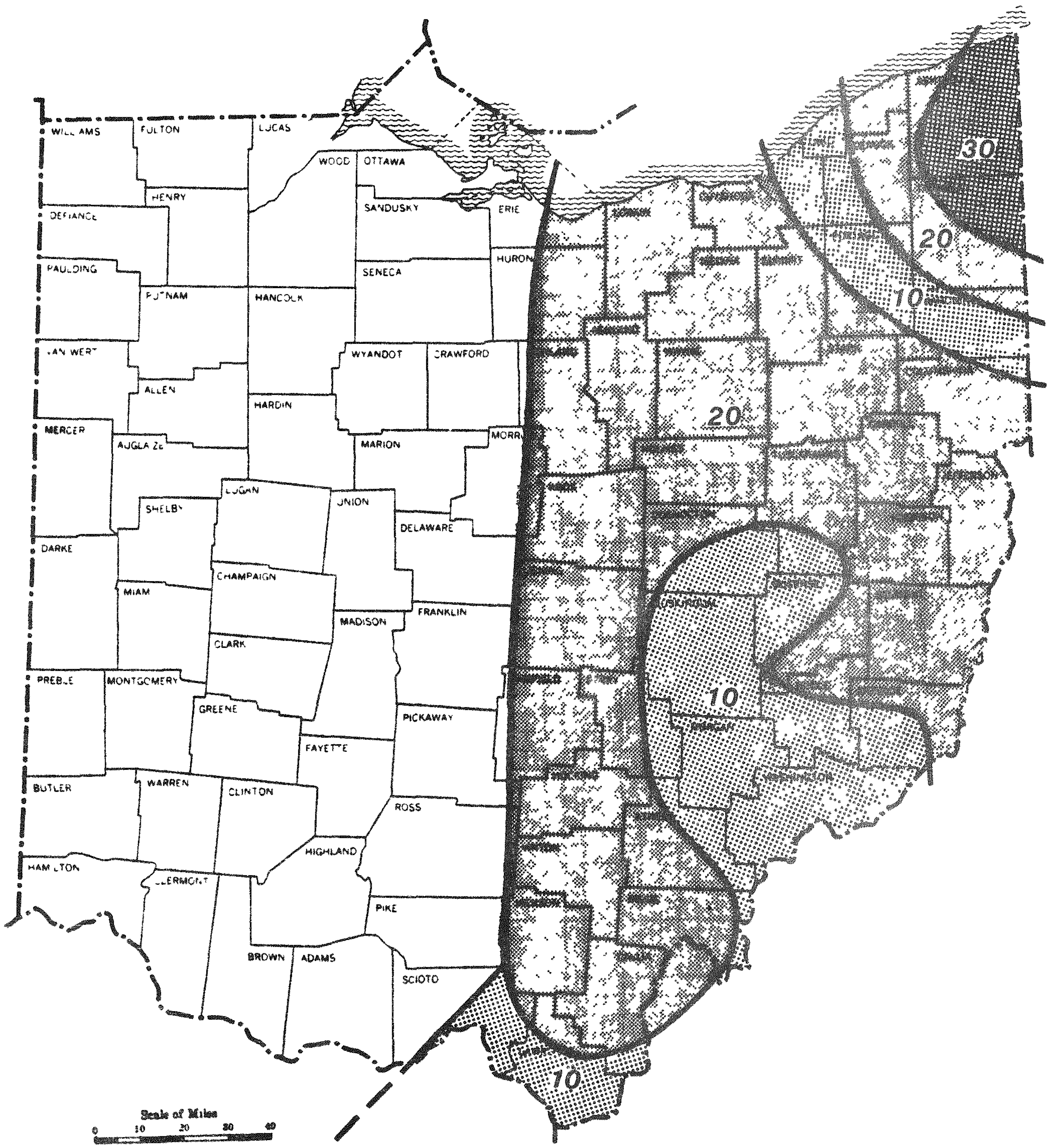
The Terra Tek data provided values of $(k_f' \cdot w_f)$ as a function of closure pressure in psi. Assuming vertical natural fractures and using predetermined values of Stress Ratio (SR) defined by:

$$SR = \frac{\text{minimum horizontal stress}}{\text{vertical stress}}$$

$$SR = \frac{(\sigma_H)_{min}}{1.15\,D}$$

Exhibit 8

NATURAL FRACTURE SPACING
(feet)



where:

D = depth, in feet

provided a means of obtaining closure pressure (CP) over the area of interest in Ohio. That is:

$$(\sigma_H)_{min} = CP = 1.15\ D\ (SR)$$

Thus, using the known stress ratio and shale depth for a given county, closure pressure, and hence the conductivity of a single natural fracture ($k_f' \cdot w_f$) could be determined.

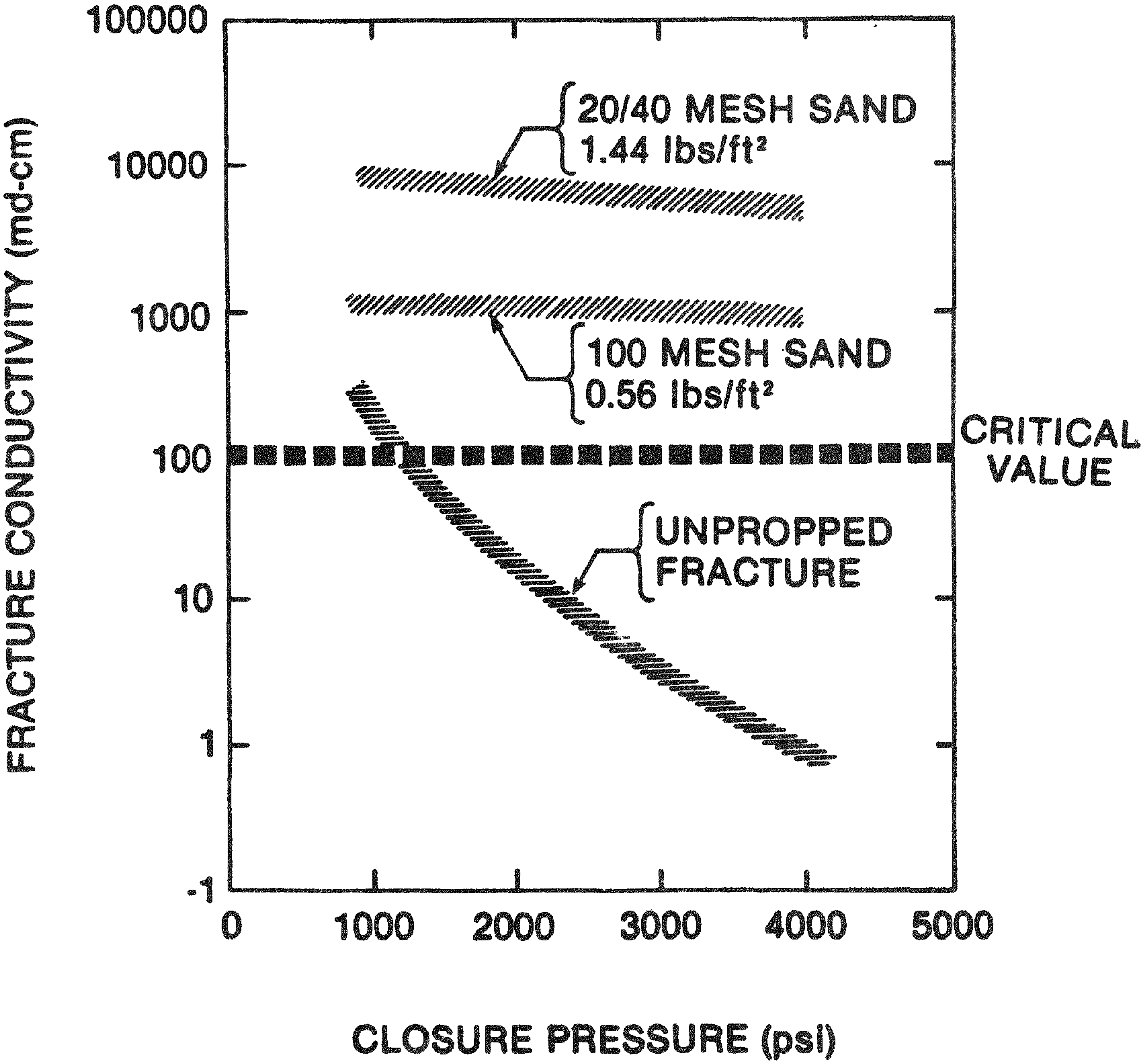
Natural fracture spacing, S, was determined over Eastern Ohio from analysis of a variety of information compiled by DOE. The calibration constant, C, was determined from the results of the Offset Well Test Program (OWTP) and core observations from a subsequently deviated well drilled near the test site. Using a calculated closure pressure of 1,560 psi in the Meigs County Well 10056, a value of 41 is derived for the product ($k_f' \cdot w_f$) from the Terra Tek fracture conductivity curve. With a bulk fracture system permeability (k_f) of .07 md, determined from the OWTP and an observed natural fracture spacing of approximately 20 feet (610 cm) in the nearby deviated well, a calibration constant of 1.04 was determined. Within experimental error, this may be taken as unity. Thus, using independently determined values of fracture spacing, natural fracture system permeability could be estimated as a function of shale depth for each study area, using the Terra Tek curve (Exhibit 9) directly.

f. Productive Thickness. Using the reservoir properties described above, the SUGAR simulator was used to history match production data to determine the remaining reservoir property, "net productive thickness".

When available, long-term production data were used for the history match. Representative wells were identified for those counties (Lawrence,

Exhibit 9

EFFECT OF PROPPANTS ON CONDUCTIVITY



Licking, and Meigs) where sufficient production data were available to characterize the resource in a statistically meaningful way. In selecting representative wells, the data base was screened to identify wells: (1) that were individually metered; (2) that had production from shale members distinguishable from other, non-shale producing horizons; (3) that included high, average, and low producers, and (4) had at least four years of production data. A detailed description of the selection of representative wells may be found in Appendix C.

When long-term production records were not available, initial open flow (IP) data and fracture permeability were utilized as part of a short-term history matching effort to arrive at productive thickness. While less confidence in results are provided by such an approach, the IP is directly proportional to the product of productive thickness and fracture permeability, and (when properly measured) gives a usable measure in absence of more stable data.

The history match of long-term production for Lawrence County is used as an example of this process, and is shown on Exhibit 10. Using the reservoir properties known for Lawrence County, the SUGAR model was employed with calculated fracture permeability to determine the net productive shale thickness that matched the initial gas flow rate as well as long-term gas production.

g. Final Data Set. A summary of the required data, their value ranges, and their sources are shown on Table 3. The table indicates three types of parameters: (1) constants, (2) variable by area, and (3) history matching. The majority of the constant data were obtained from the OWTP and EGSP core wells, while the large portion of the variable data was derived from the Mound and Cliffs Minerals reports. The reservoir data required to run the borehole shooting case is shown by county in Table 4.

Exhibit 10

HISTORY MATCH --
REPRESENTATIVE LAWRENCE COUNTY WELL

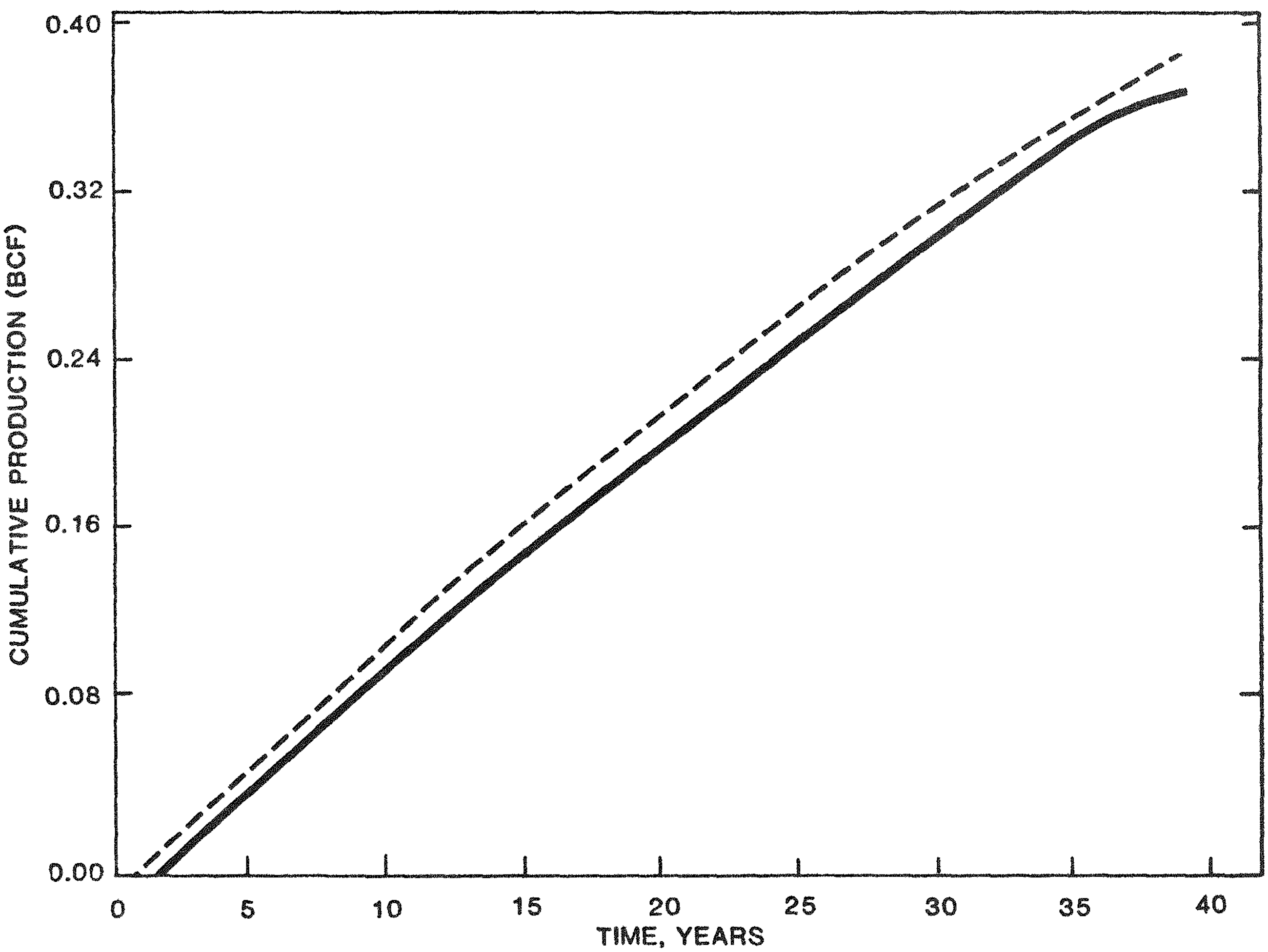


TABLE 3
REQUIRED RESERVOIR PARAMETERS

A. Constants	Representative Value or Range	Source
Drainage Area, A	160 Acres	Historical Production
Matrix Permeability, k_m	5×10^{-6}md	Core Analysis & Simulation
Matrix Porosity, Φ_m	0.01	Offset Well Test; Core Analysis
Fracture Porosity, ϕ_f	0.0009	Offset Well Test
B. Variables, By Area		
Fracture Permeability, k_f	0.02 - 4 md	Laboratory Tests (Terra Tek); Stress Ratio (DOE/METC)
Gas Content, G_c	10 - 220 Mcf/AF	Mound Report
Initial Pressure, P_i	65 - 815 psia	Well Records
Line Pressure, P_l	25 - 100 psia	Estimated
Fracture Spacing, a	10 - 30 feet	Cliffs Minerals Report; Stress-Ratio Map
C. Matching Parameters		
"Productive Interval," h	10 - 120 feet	Simulation

TABLE 4
RESERVOIR PROPERTIES FOR OHIO COUNTIES

County	Depth (feet)	Temp (F°)	Pressure (psia)	Frac Spac (feet)	GC (Mcf/AF)	Matrix Perm. (k_f)
Ashland	1315	67.1	215	20	175	.2133
Ashtabula	1365	67.7	85	30	60	.0200
Athens	2465	82.0	615	20	60	.0200
Belmont	4210	104.7	765	20	10	.0200
Carroll	3145	90.9	540	20	35	.0200
Columbiana	3355	93.6	715	20	30	.0200
Coshocton	2135	77.8	390	10	70	.4429
Cuyahoga	1090	64.2	65	20	175	.2789
Erie	360	54.7	65	20	220	4.4291
Fairfield	1180	65.4	290	20	90	.2133
Gallia	2460	82.0	715	20	100	.0200
Geauga	1545	70.1	90	20	110	.0591
Guernsey	3560	96.3	525	20	20	.0200
Harrison	3410	94.3	640	20	15	.0200
Hocking	1605	70.9	415	20	85	.0498
Holmes	2050	76.7	340	20	100	.0254
Huron	365	54.7	90	20	200	4.4291
Jackson	1515	69.7	470	20	50	.0574
Jefferson	3465	95.0	815	20	15	.0200
Knox	1315	67.1	290	20	110	.2100
Lake	1300	66.9	65	20	125	.1247
Lawrence	2320	80.2	690	10	100	.0276
Licking	1500	69.5	240	20	90	.2993
Lorain	960	62.5	73	20	200	.5085
Mahoning	2805	86.5	365	10	40	.0200
Medina	1490	69.4	95	20	170	.0951
Meigs	2740	85.6	775	20	80	.0771
Monroe	4715	111.3	765	10	5	.0200
Morgan	2990	88.9	615	10	15	.0886
Muskingum	2425	81.5	415	10	40	.2362
Noble	3755	98.8	735	10	15	.0387
Perry	1945	75.3	415	20	45	.0213
Portage	1995	75.9	140	10	95	.0427
Richland	1105	64.4	275	20	175	.4921
Stark	2120	77.6	315	20	80	.0200
Summit	1725	72.4	111	20	125	.5020
Trumbull	2135	77.8	135	20	50	.0200
Tuscarawas	2660	84.6	485	20	55	.0200
Vinton	1615	71.0	460	20	100	.0476
Washington	4515	108.7	815	10	10	.0223
Wayne	1660	71.6	215	20	140	.0574

C. DEVELOPMENT OF REPRESENTATIVE DATA FOR EACH REGION

The parameters required for the stimulation cases, beyond those required for the borehole shooting case, include:

- Fracture permeability expressed in x-and-y components to reflect permeability anisotropy;
- Angle of intersection between the induced and natural fractures;
- Pressure gradients in the stimulation geometry; and,
- Drainage pattern shape.

These were determined for each of the six partitioned areas of Ohio. The rationale for partitioning is discussed in the following chapter.

1. Horizontal Stress

Horizontal stress was used here to indicate the preferred orientation direction of induced fractures. In-situ stress field components were determined and mapped based on data by Cliffs Minerals. Stress from a shallow well test and stress from a surface test were plotted. The resulting map provided results of in-situ stress measurements made in the basin and indicate maximum horizontal stress. The Cliffs' work on stress measurements were reviewed and generalized directional trends were plotted for Ohio, as shown in Exhibit 11.

2. Natural Fracture Orientation

The fracture orientations were mapped using fracture logs compiled by Cliffs Minerals. The log records indicate the strike and dip for each natural fracture. All EGSP core wells located in Ohio, which were included

Exhibit 11

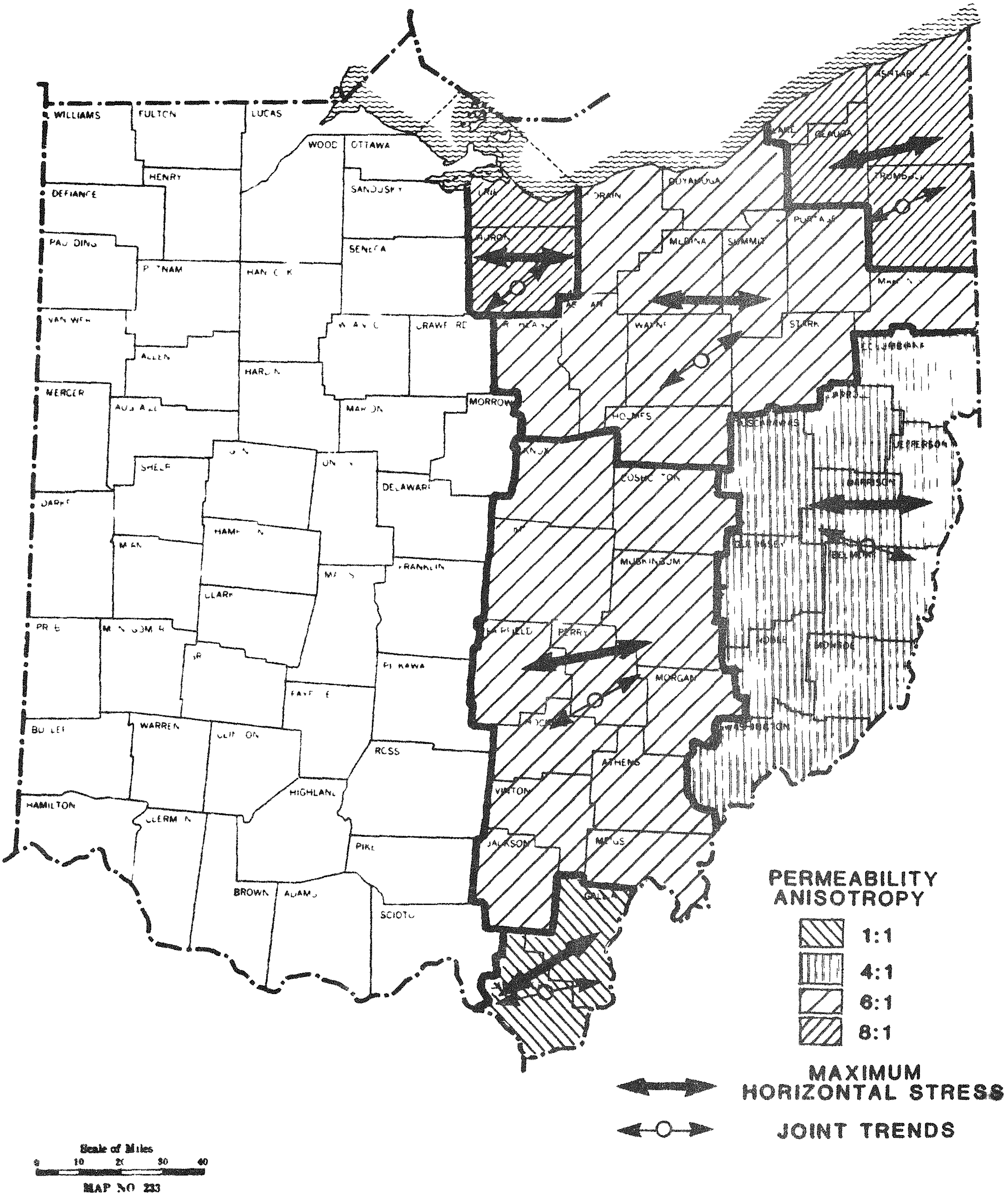
HORIZONTAL STRESS TRAJECTORIES

Scale of Miles

— — HORIZONTAL STRESS TRAJECTORIES

Exhibit 12

REGIONAL ORIENTATIONS NATURAL vs. INDUCED FRACTURES



in the Cliffs report series, were considered. The log records were reviewed and the strike and dip were tabulated per natural fracture within a specific Devonian shale member. The tabulated results allowed identification and labeling of the major and minor natural fracture direction. The resulting directions were mapped and are shown in Exhibit 12. The angle between the induced and natural fractures was determined by area and is shown below:

Major Natural Fracture and Induced Fracture Orientations

Partitioned Area	Angle (Degrees)
I	30
II	10
III	20
IV	40
V	40
VI	40

3. Permeability Anisotropy

Permeability anisotropy was determined for each partition area from the relative intensity of the major and minor natural fractures. Thus, a ratio of the major and minor natural fractures was identified.

Directional Permeability Ratio

Partitioned Area	Ratio ($k_x:k_y$)
I	1:1
II	6:1
III	4:1
IV	6:1
V	8:1
VI	8:1

The permeability in the x and y directions was then calculated for input into the SUGAR Simulator.

4. Reservoir Properties by Area

The data aggregated from the data compilations and analyses are summarized on Table 5, as follows:

TABLE 5

AVERAGE GEOLOGIC PROPERTIES BY AREA

Partitioned Area	Frac. Spacing (feet)	Perm. Anisotropy (ratio)	Intersect Angle (degrees)
I	10	1:1	N/A
II	20	6:1	10
III	20	4:1	20
IV	20	6:1	40
V	20	8:1	40
VI	20	8:1	40

IV. PARTITIONING THE STATE

The partitioning of Ohio considered both regional geology, tectonophysics and gas production trends. The tectonophysics of the region include detachment limits as well as fracture orientation and permeability geologic characteristics. The geologic characteristics were derived primarily from analyzing the Cliffs Minerals study and included:

- Horizontal Stress (Exhibit 11)
- Permeability Anisotropy (Exhibit 12)
- Natural Fracture Orientation (Exhibit 13)
- Mechanical Fabric of the Shales (Exhibit 14)

These characteristics have been discussed in detail in the previous chapter. Along with the geologic characteristics, the projected average 40-year cumulative production estimate was used as a parameter in partitioning.

These factors were then analyzed using a trend surface analysis approach and the resulting partition of Ohio is shown in Exhibit 15. This form of analysis attempts to group counties with similar characteristics together, while minimizing the variation of a single characteristic within the group. Counties which exhibited regional geologic trends similar to two areas were included in the area where the gas production or rock pressure characteristics would cause the least variation within the group.

Exhibit 13

NATURAL FRACTURE ORIENTATION

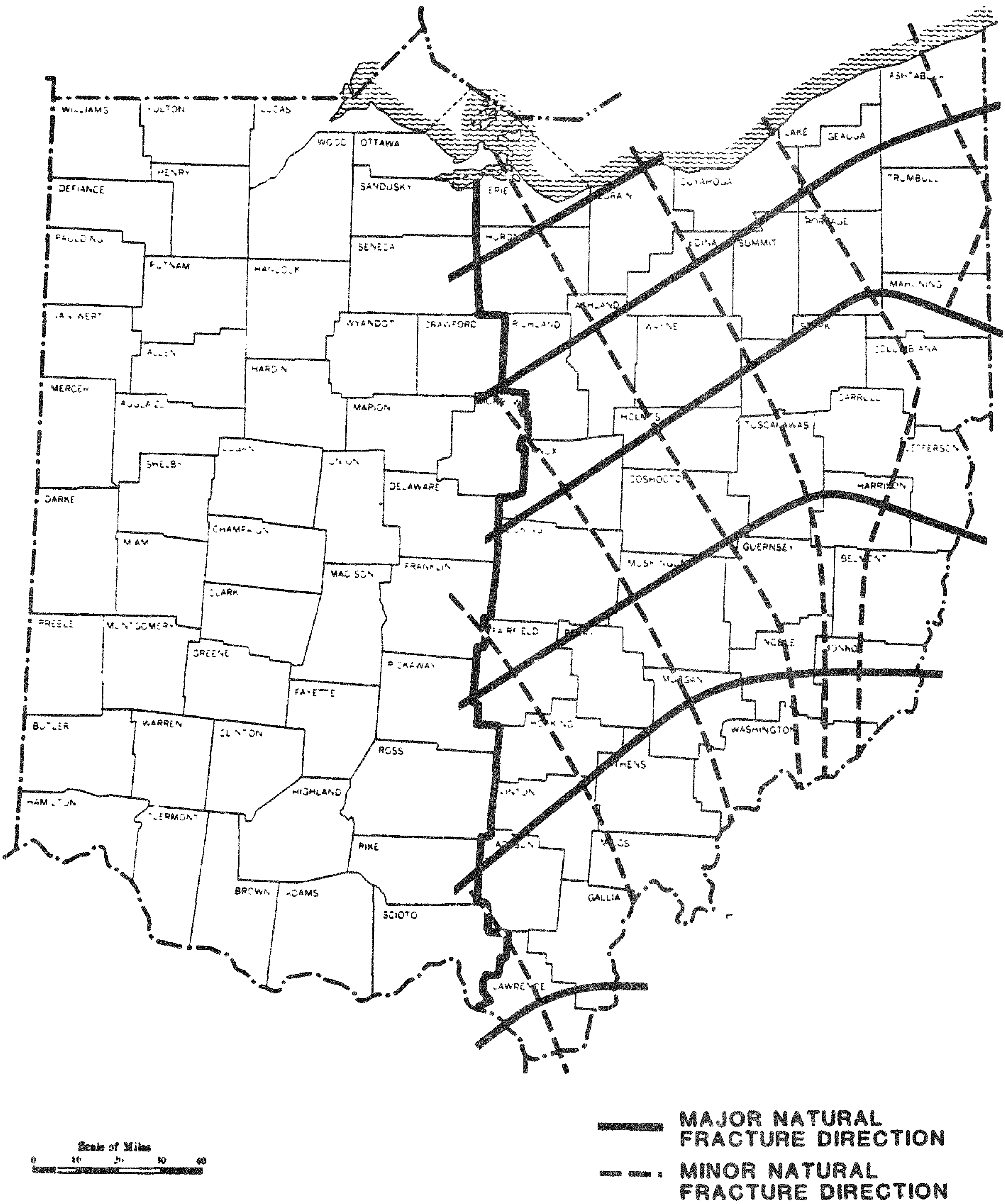


Exhibit 14

MECHANICAL FABRIC TREND IN SHALE

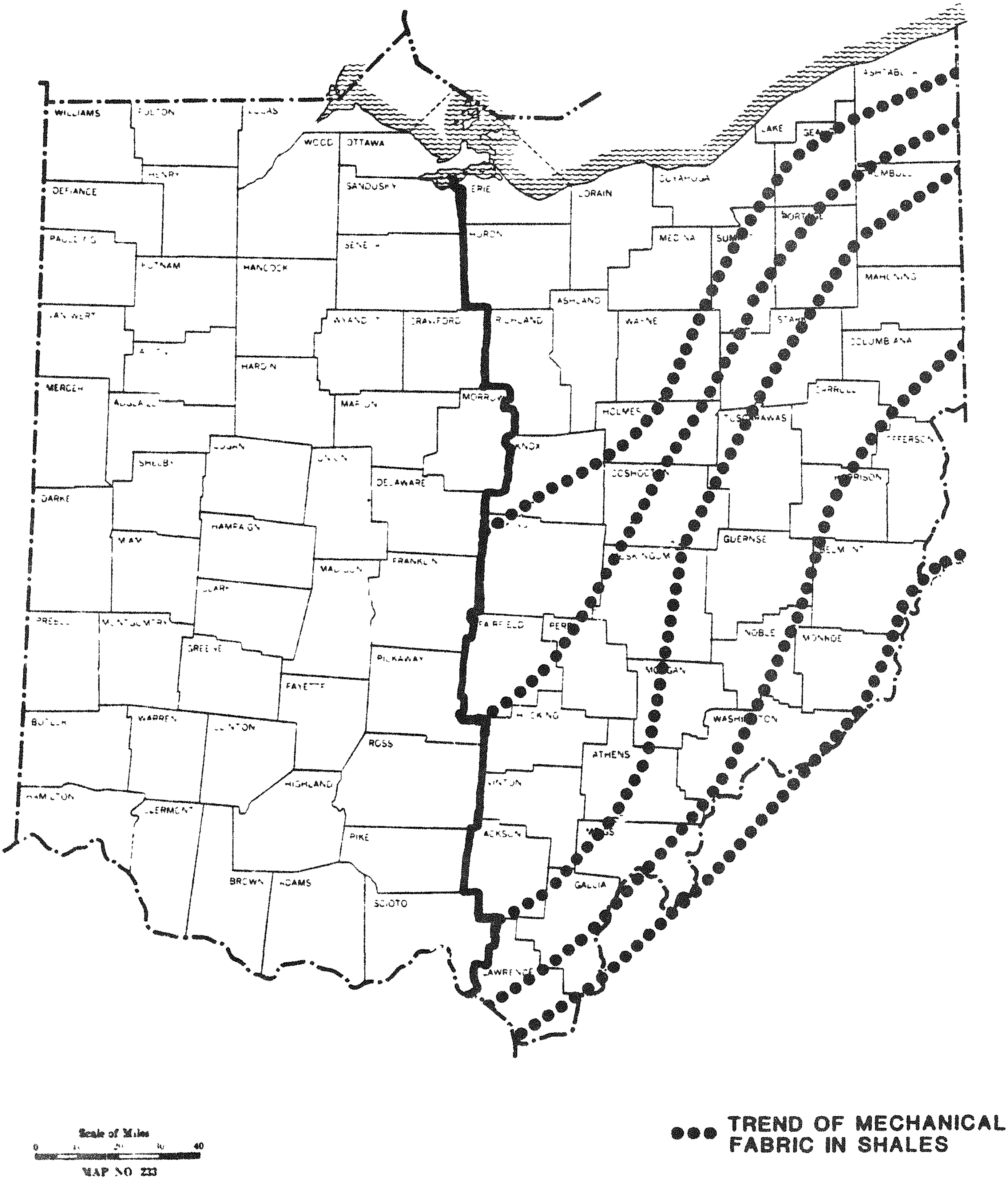
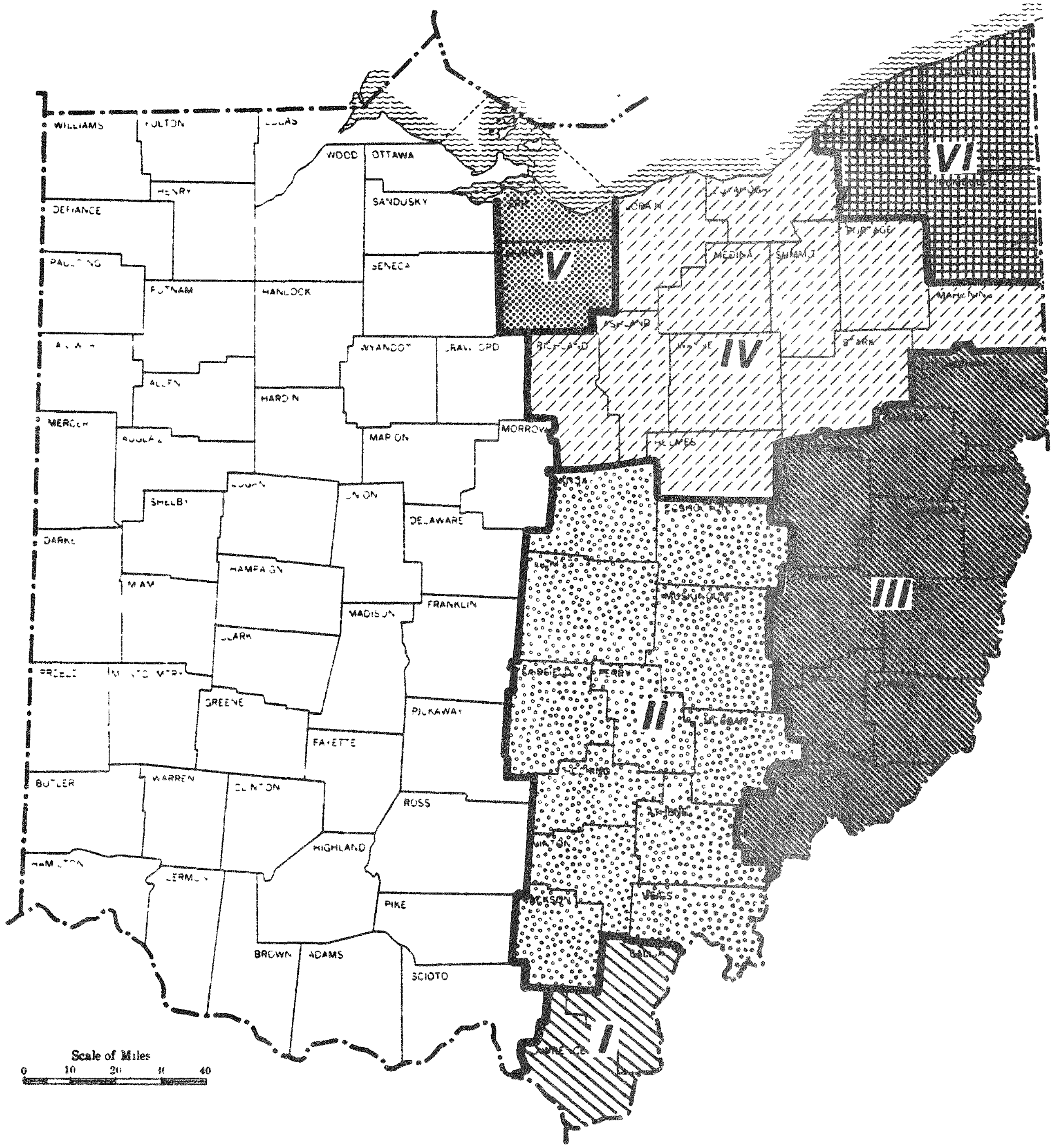


Exhibit 15

PRIMARY PARTITIONED AREAS DEVONIAN GAS SHALES OF OHIO



V. RESERVOIR MODELING AND WELL STIMULATION

This chapter describes the reservoir model used by the study, provides a brief review of the advanced well stimulation cases analyzed, and presents basic information on the procedures used to model the stimulation cases.

A. SUGAR MODEL

The model used for the history match is the two-dimensional numerical model (SUGAR-MD) available at DOE/METC. This model was developed specifically for analyzing Devonian Shale production and includes the three key sources for gas storage and production; namely:

- The macro-fracture system,
- The micro-fracture system, and
- Gas adsorbed on the organic kerogen in the shale.

The SUGAR model describes the transient pressure response of a naturally fractured reservoir by two dimensionless parameters: the dimensionless fracture storage coefficient, ω, and the dimensionless fracture transfer coefficient, λ. These are defined as follows:

- The dimensionless fracture storage coefficient, ω, is defined as:

$$\omega = \frac{\Phi_f}{\Phi_f + \Phi_m}$$

where: Φ_f = fracture porosity
Φ_m = matrix porosity

- The dimensionless fracture transfer coefficient, λ, is defined as:

$$\lambda = \frac{8}{a^2}\left[\frac{k_m}{k_f/r_w^{\,2}}\right]$$

where: 2a = fracture spacing
k_f = fracture permeability
k_m = matrix permeability
r_w = well-bore radius

The two dimensionless parameters used by the SUGAR simulator establish a direct relationship between certain of the reservoir parameters. The dimensionless transfer coefficient, λ, determines the interdependence between k_m, k_f, and r_w. This means that unless two of these parameters are known with certainty, the third cannot be determined as an independent value from history matching. In addition, any uncertainty in the magnitude of one of the parameters will have a direct effect on the value of one or both of the other parameters.

In addition, there are two unconventional gas storage parameters:

- h = "net productive" interval
- G_c = adsorbed gas content

The proper selection of values for these parameters can lead to a highly accurate history matching of actual gas production.

B. DELINEATION OF STIMULATION CASES

Five well stimulation techniques were evaluated for their applicability to Ohio Devonian shales:

- Borehole Shooting (r'_w = 1.8 feet): currently the most frequently used technique in the Devonian shales;
- Small Radial Stimulation (r'_w = 30 feet): attainable with emerging technological improvements such as omni-directional stimulation;
- Large Radial Stimulation (r'_w = 60 feet): potentially attainable with major improvements in explosive and propellant technology;
- Small Vertical Fracture (x_f = 150 feet): attainable, but not yet fully controllable or predictable with current technology; and
- Large Vertical Fracture (x_f = 600 feet): potentially attainable with significant advances in technology or alternate fracture fluids and proppants.

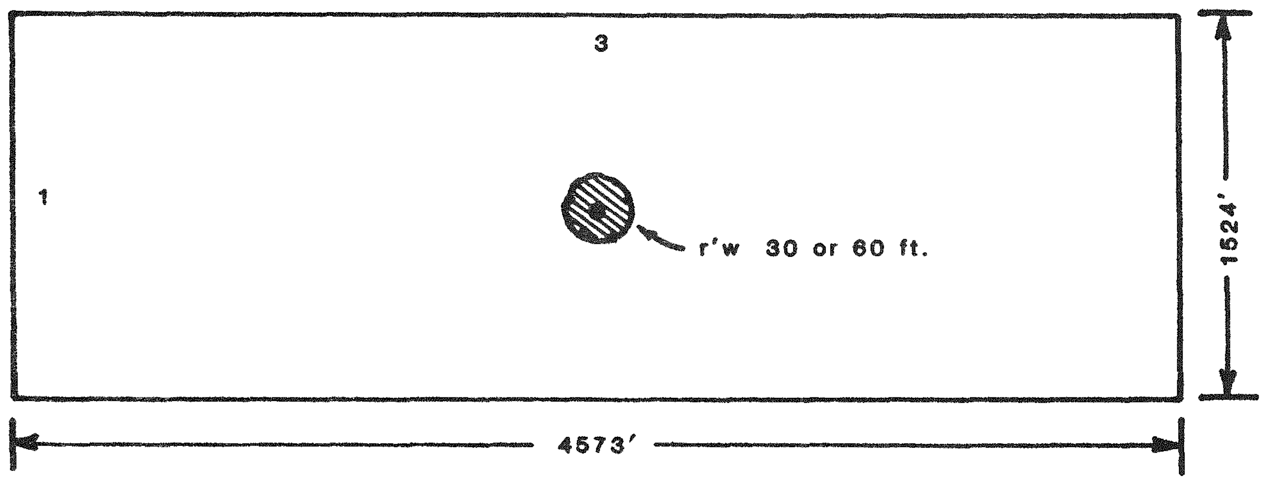
A schematic of radial and vertical stimulation techniques appears in Exhibit 16.

Exhibit 16

STIMULATION TREATMENT SCHEMATICS

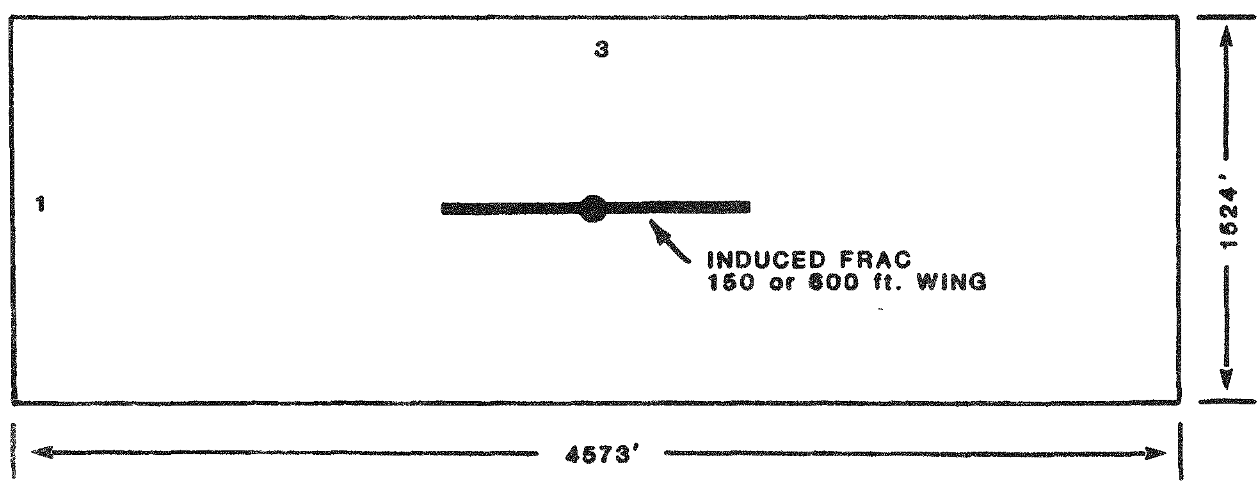
RADIAL STIMULATION SCHEMATIC
(Not to Scale)

160 Acres



INDUCED FRACTURE SCHEMATIC
(Not to Scale)

160 Acres



C. MODELING OF STIMULATION CASES

Each of the stimulation cases requires an x-y grid-block layout in the SUGAR Simulator to accommodate the radial or induced fracture design.

The variable pressure blocks which drive the radial stimulation cases are a function of line pressure and well depth. The fracture geometry for the radial stimulations was designed for effective wellbore radii of 30 and 60 feet, with line pressure applied out to the radius of the stimulation in both radial cases, which therefore assumes infinite conductivity from the wellbore to the tip of the radius. In the vertical fracture cases, the fracture is assumed to have infinite conductivity along the length of the wing and the line pressure is applied along the entire distance.

To properly model induced vertical fractures, variable rate blocks must be specified. The rate blocks are a function of line pressure, productivity index, and well depth. The productivity index in turn is dependent on the following factors:

- Block size in the direction of the induced fracture,
- Block size in the direction perpendicular to the induced fracture,
- Fracture permeability in the direction perpendicular to the induced fracture, and
- Productive shale thickness.

VI. TECHNICALLY RECOVERABLE GAS

A. SUMMARY

The Devonian shales of Ohio (Lower Huron member) offer an important future source of natural gas. The target intervals analyzed by this study contain an estimated 50 Tcf of gas in-place. Recent research shows that a major portion of this gas may be feasible to recover, as discussed below:

- Total gas in-place in the Devonian shales of Ohio is large, amounting to nearly 390 Tcf. The Huron interval accounts for approximately two thirds of this total, or over 250 Tcf. The selected portions of Middle and Lower Huron members, the vertical sequence historically completed in the Ohio shales, and the target interval for this study, contain nearly 50 Tcf.

- The technically recoverable gas from the target sequence of Devonian shales of Ohio ranges from 6.2 to 22.5 Tcf. The low end of the range reflects well stimulation by borehole shooting and current field development practices. The high end of the range reflects application of advanced stimulation technology (vertical fracturing and radial stimulation) and use of alternative field development methods.

- Gas recovery and flow rates per well vary widely, with highest recoveries in southern Ohio. Highest gas production rates and ultimate recovery can be expected in southern Ohio (Area I). Gas recoveries per well can reach 1,000 MMcf (40 year cumulative recovery with large, 600-foot half length, vertical fractures) with gas flow rates of 200 Mcf per day (daily average for first four years). Lowest recovery and gas flow rates are in northeast Ohio (Area VI). Here ultimate recovery is estimated at 24 MMcf (40-year cumulative recovery with 60-foot radial stimulation) with gas flow rates of 2 Mcf per day.

- It will take a major drilling effort, from 44 to 88 thousand wells, to produce the technically recoverable gas in Ohio. Given an undrilled, accessible area of nearly 11,000 square miles (over 7 million acres), it would take 43,970 wells on 160-acre spacing, or 87,940 wells on 80-acre spacing, to fully develop and produce the technically recoverable gas in the Devonian shales (Lower Huron member) of Ohio.

- Improved stimulation technology is required to unlock the full gas potential. Use of large vertical fractures, in the high gas potential Area I, will provide per well cumulative recoveries (over 40 years) of 1,080 MMcf versus 386 MMcf by borehole shooting. Even in the low gas potential Area VI, large radial stimulation would more than double the gas flow rates and ultimate recovery as compared with borehole shooting. Future technical advances for more efficiently interconnecting the natural fracture system to the well drainage area would further add to gas recovery.

- Alternative well spacing and pattern configuration will also help increase gas recovery. Reduced well spacing, to 80 acres per well, will substantially increase gas recovery--from 15.2 Tcf at 160 acres to 22.5 Tcf at 80 acres--without appreciably reducing recovery in the initial years. In addition, changing the pattern alignment to a 3 by 1 rectangle from the traditional square pattern improves gas recovery per well by 5 to 10 percent.

These findings are further discussed in the following sections and assume that prudent drilling and completion practices will be adhered to and that the wells are properly sited.

B. GAS IN-PLACE

Total gas in-place in the Devonian shales of Ohio is large, amounting to nearly 390 Tcf. Of this total, the Huron interval accounts for approximately 250 Tcf. The net productive interval or "target interval" in the Middle and Lower Huron units contain nearly 50 Tcf in the six partitioned areas of Ohio, with Area IV alone containing 25 Tcf. The target interval is composed of the vertical shale sequence, which was determined to be productive through simulation with the SUGAR model. Gas in-place is shown by partitioned area and interval below:

TABLE 6

TOTAL GAS IN-PLACE

Partitioned Area	Gas In-Place All Intervals (Tcf)	Gas In-Place Huron Interval (Tcf)	Gas In-Place Target Interval (Tcf)
I	16.0	13.0	4.1
II	106.4	78.9	12.4
III	119.2	53.1	4.4
IV	101.4	78.1	24.8
V	9.0	8.6	0.4
VI	36.9	21.8	3.3
TOTAL	388.9	253.5	49.4

The gas in-place is contained in three sources:

- Free matrix gas is that gas which fills small micro-fractures and other small matrix porosities;
- Sorbed matrix gas is that gas absorbed or adsorbed by the organic matter in the shale; and,
- Free fracture gas is that gas filling the major fractures and joint systems.

The gas content data determined by Mound were used in this study to calculate the free matrix and sorbed matrix gas contents. The Mound data contain the total gas content in the matrix and were provided in Mcf/acre-foot. To calculate the free matrix portion of the gas, the following equation was used:

$$G_c = \frac{-35.37}{T} \cdot \Phi_m \cdot \frac{P_i}{Z_i}$$

where: G_c = Gas Content (Mcf/AF)
T = Reservoir temperature (^oR)
Φ_m = Matrix porosity (decimal)
P_i = Initial rock pressure (psia)
Z_i = Z factor

Once the free matrix gas has been calculated, the sorbed matrix gas may be calculated as the difference between the Mound number and the free matrix gas. The free fracture gas is determined assuming complete gas saturation in the fractures.

The major portion of the gas is from the sorbed matrix portion in all areas of Ohio except Area III, where the gas content is extremely low. The percentage of gas by source has been compiled in Table 7.

TABLE 7

GAS IN-PLACE BY GAS SOURCE, FOR HURON TARGET INTERVAL

Partitioned Area	GAS IN-PLACE (% of Total, By Area)		
	Free Fracture (%)	Free Matrix (%)	Sorbed Matrix (%)
I	2	23	75
II	1	8	91
III	7	75	18
IV	*	5	95
V	*	1	98
VI	1	8	91
OVERALL	1	14	85

Partitioned Area	GAS IN-PLACE (Tcf, By Area)			
	Free Fracture (Tcf)	Free Matrix (Tcf)	Sorbed Matrix (Tcf)	Total (Tcf)
I	0.1	1.0	3.0	4.1
II	0.1	1.0	11.3	12.4
III	0.3	3.3	0.8	4.4
IV	0.1	1.1	23.6	24.8
V	**	**	0.4	0.4
VI	**	0.3	3.0	3.3
TOTAL AREA	0.6	6.7	42.1	49.4

*Less than 0.5%

**Less than 0.05 Tcf

C. DISCUSSION OF RECOVERABLE GAS AND RECOVERY EFFICIENCY

Recoverable gas in Ohio ranges from 6.2 to 15.2 Tcf in 40 years, for wells drilled on 160-acre spacing, as shown on Table 7, below. Drilling on an 80-acre spacing could increase recoverable gas to 22.5 Tcf over 40 years. (The potential for alternative well spacing is further discussed in Chapter VII, Other Factors Affecting Production.)

TABLE 8

TECHNICALLY RECOVERABLE GAS, BY AREA AND STIMULATION METHOD

			Technically Recoverable Gas (Tcf) in 40 Years				
Partitioned Area	Total Drillable Area (Sq. Mi.)	Gas In-Place (Tcf)	Borehole Shooting	Small Radial Stim. r'w=30'	Large Radial Stim. r'w=60'	Small Vertical Fracture xf=150'	Large Vertical Fracture xf=600'
I	543	4.1	0.84	1.16	1.41	1.58	2.35
II	3,577	12.4	2.95	4.06	4.64	4.67	6.21
III	2,869	4.4	1.46	1.98	2.25	2.33	3.04
IV	2,641	24.8	0.84	1.35	1.73	1.78	3.38
V	313	0.4	0.05	0.06	0.06	0.06	NA
VI	1,035	3.3	0.04	0.07	0.10	0.09	0.20
TOTAL	10,978	49.4	6.18	8.68	10.19	10.51	15.18

Overall recovery efficiency, as percent recovery of gas in-place, ranges from 13% with borehole shooting to 31% with large vertical fracturing of the Ohio Devonian shales. Relatively high recovery efficiencies of 50% to 60% appear attainable in Areas I, II and III; much lower efficiencies of 6 to 16% are representative of Areas IV, V and VI, as shown on Table 9.

TABLE 9

RECOVERY EFFICIENCY BY AREA AND STIMULATION METHOD

(Percent Recovery of Gas In-Place [Lower Huron] in 40 Years)

	Well Stimulation Method				
Partitioned Area	Borehole Shooting	Small Radial Stimulation r'_w=30'	Large Radial Stimulation r'_w=60'	Small Vertical Fracture x_f=150'	Large Vertical Fracture x_f=600'
I	20	28	34	38	57
II	24	33	38	38	50
III	33	45	51	53	69
IV	3	6	7	7	14
V	12	15	16	16	NA
VI	1	2	3	3	6
OVERALL	13	18	21	23	31

With advanced stimulation, overall recovery efficiency is 52% for the free gas in-place in the fracture and the matrix system. However, only about 27% of the gas absorbed in the organic kerogen is produced in 40 years, as shown in Table 10.

TABLE 10

GAS RECOVERY EFFICIENCY BY AREA AND GAS SOURCE

(With Advanced Stimulation)

Partitioned Area	Free Gas In Fractures (%)	Free Gas In Matrix (%)	Sorbed Gas In Matrix (%)	Total (%)
I	59	61	54	57
II	57	52	50	50
III	69	70	67	69
IV	18	14	14	14
V	51	17	16	16
VI	7	6	6	6
OVERALL	58	54	27	31

The relative contributions of the three in-place sources to technically recoverable gas (with advanced stimulation) are as follows:

Source of Gas	Gas In-Place (Tcf)	Technically Recoverable (Tcf)	Technically Recoverable (% In-Place)
• Free gas in fractures	0.6	0.4	58
• Free gas in matrix	6.7	3.5	54
• Sorbed gas in matrix	42.1	11.3	27
TOTAL	49.4	15.2	31

The contribution of the three sources to technically recoverable gas, by area, is shown on Table 11.

TABLE 11

TECHNICALLY RECOVERABLE GAS, BY AREA AND GAS SOURCE (Tcf)

(With Advanced Stimulation)

Partitioned Area	Free Gas In Fractures (Tcf)	Free Gas In Matrix (Tcf)	Sorbed Gas In Matrix (Tcf)	Total (Tcf)
I	0.1	0.5	1.7	2.3
II	0.1	0.5	5.6	6.2
III	0.2	2.3	0.5	3.0
IV	*	0.2	3.2	3.4
V	*	*	0.1	0.1
VI	*	*	0.2	0.2
TOTAL	0.4	3.5	11.3	15.2

*Less than 0.1 Tcf

D. TECHNICALLY RECOVERABLE GAS, BY WELL

1. Cumulative Recovery

Cumulative gas recovery per well using advanced stimulation is highest (at 1,080 MMcf) in Area I and lowest in Area VI (at 47 MMcf). Table 12 shows the near-term gas recovery (5 and 10-year cumulatives) and the long-term (40-year cumulatives) per well, for each of the alternative stimulation methods, assuming 160-acre spacing. The general trend of cumulative producting using bare hold shooting is illustrated in Exhibit 17.

2. Daily Production Rates

First year gas production rates range from 238 Mcf/D in Area I with a large vertical fracture, to about 1 Mcf/D in Area VI using borehole shooting. The gas production rate is highly sensitive to stimulation treatments, as shown on Table 13.

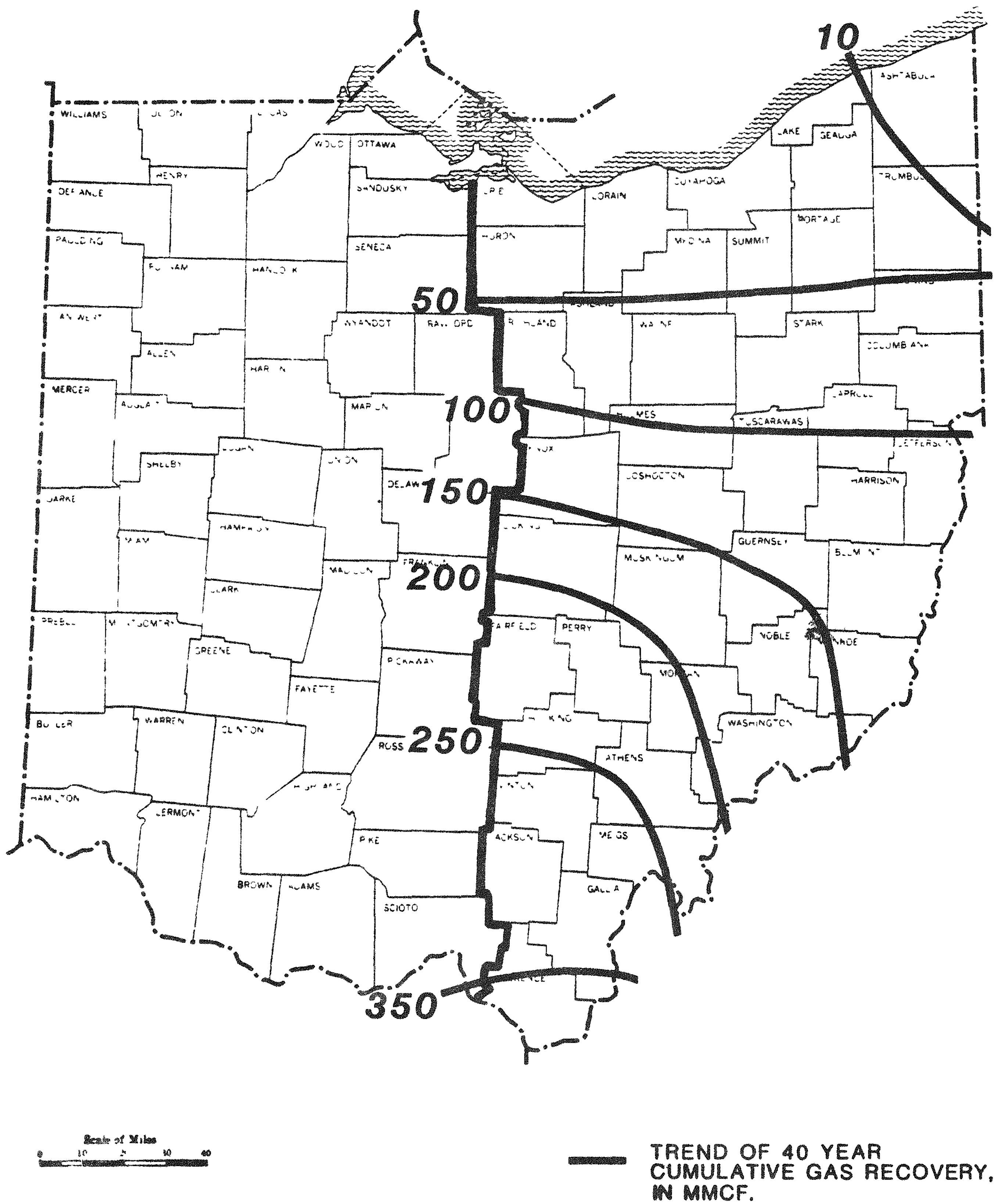
The data for Area I show that large vertical fractures can increase the gas production rate by nearly sevenfold in year 1 and by fourfold in year 5, over borehole shooting. In addition to the benefits of early production stimulation, ultimate recovery (in 40 years) is increased nearly threefold:

Gas Production Rate	Borehole Shooting	Large Vertical Fracture	Increase of Vertical Fracture Over Borehole Shooting (x-fold)
(Mcf/D)			
--Year 1	36	238	6.6
--Year 5	31	123	4.0
Ultimate Recovery (MMcf)	386	1,080	2.8

Similar increases in gas flow and recovery are evident in all of the areas of Ohio except in Area V, where fracture permeability is already high, thus dampening the benefits of extensive well stimulation.

Exhibit 17

CUMULATIVE GAS PRODUCTION TREND (With Borehole Shooting)



TREND OF 40 YEAR CUMULATIVE GAS RECOVERY, IN MMCF.

TABLE 12

PER WELL GAS RECOVERY, BY AREA AND STIMULATION METHOD

(Cumulative Recovery, MMcf)

	Borehole Shooting	Small Radial Stimulation $r'_w = 30'$	Large Radial Stimulation $r'_w = 60'$	Small Vertical Fracture $x_f = 150'$	Large Vertical Fracture $x_f = 600'$
AREA I					
5 Years	61.3	96.3	129.3	161.3	344.1
10 Years	116.1	176.5	230.1	276.4	529.7
40 Years	386.4	536.1	650.4	729.8	1,080.0
AREA II					
5 Years	33.7	52.8	65.0	66.4	110.1
10 Years	64.3	98.0	118.6	120.7	189.6
40 Years	206.0	283.8	324.4	326.6	433.9
AREA III					
5 Years	22.3	36.1	45.7	49.6	92.0
10 Years	41.8	64.5	79.4	84.8	142.2
40 Years	127.2	172.1	196.0	202.8	265.3
AREA IV					
5 Years	10.7	18.4	24.4	25.6	55.8
10 Years	21.1	35.6	47.0	49.0	103.4
40 Years	79.1	127.9	163.9	168.4	320.0
AREA V					
5 Years	5.6	7.0	7.7	7.5	NA
10 Years	10.8	13.6	14.8	14.5	NA
40 Years	38.8	47.2	51.0	51.0	NA
AREA VI					
5 Years	1.3	2.6	3.6	3.5	8.4
10 Years	2.6	5.0	6.9	6.6	15.4
40 Years	9.8	17.7	23.6	22.4	47.0

TABLE 13

PER WELL GAS PRODUCTION RATES, BY AREA AND STIMULATION METHOD

(Daily Production, Mcf/D)

	Borehole Shooting	Small Radial Stimulation $r'_w = 30'$	Large Radial Stimulation $r'_w = 60'$	Small Vertical Fracture $x_f = 150'$	Large Vertical Fracture $x_f = 600'$
AREA I					
5 Years	31	47	60	70	123
10 Years	29	42	52	59	90
40 Years	21	26	29	30	29
AREA II					
5 Years	18	27	33	33	51
10 Years	16	23	28	28	39
40 Years	10	13	13	13	13
AREA III					
5 Years	11	17	21	22	35
10 Years	10	15	17	18	24
40 Years	6	7	7	7	5
AREA IV					
5 Years	6	10	13	13	28
10 Years	6	9	12	12	25
40 Years	5	8	10	10	17
AREA V					
5 Years	3	3.7	4	4.0	NA
10 Years	3	3.5	3.8	3.8	NA
40 Years	2.3	2.7	2.9	2.8	NA
AREA VI					
5 Years	0.7	1.4	1.9	1.8	4.2
10 Years	0.7	1.3	1.7	1.7	3.7
40 Years	0.6	1.1	1.4	1.3	2.5

E. DRILLING AREA AND DRILLING POTENTIAL

The undrilled and accessible area of Ohio, underlaid by Devonian age gas-bearing shales, is 10,978 square miles, or 7,025,920 acres, distributed by partitioned area as follows:

	Total Drillable Area	
	Square Miles	Acres
Area I	543	347,520
Area II	3,577	2,289,280
Area III	2,869	1,836,160
Area IV	2,641	1,690,240
Area V	313	200,320
Area VI	1,035	662,400
TOTAL	10,978	7,025,920

The number of wells required to "drill up" the 10,978 square miles of still undrilled and accessible area of Ohio would be 43,911 to 87,822, depending on the pattern spacing selected by the operator, as shown below:

Partitioned Area	Total Drillable Area (M Acres)	Total Required Wells	
		At 160-Acre Spacing/Well	At 80-Acre Spacing/Well
Area I	348	2,172	4,344
Area II	2,289	14,308	28,616
Area III	1,836	11,475	22,950
Area IV	1,690	10,563	21,126
Area V	200	1,252	2,504
Area VI	6,621	4,141	8,282
TOTAL	7,026	43,911	87,822

F. NEED FOR AND VALUE OF ADVANCED WELL STIMULATION TECHNOLOGY

Analysis shows that advanced stimulation methods add significant additional gas over borehole shooting. Previously, it had been assumed that merely linking the natural fracture system to the wellbore was sufficient to achieve efficient gas recovery, and that the greater the number of natural fractures connected, the greater the resulting gas recovery.

This analysis showed, however, that a higher conductivity path than provided by the natural fracture system is required to achieve efficient gas flow rates. This is because the permeability in the natural fracture system is too low (0.02 to 0.30 md) to provide adequate conductivity; thus, an induced fracture with proppants and high conductivity is required for efficient gas recovery.

The expected increase in gas productivity, due to the application of advanced well stimulation, must be weighed against the extra cost of the stimulation treatment. One method for so doing is to determine if the additional expense of the stimulation treatment could be paid back over a specified period of time.

The table below indicates the incremental gas production (MMcf) over borehole shooting in Areas I and II in 5 years:

Type of Stimulation	Incremental Gas Recovery, In Five Years, Over Borehole Shooting (MMcf/Well)	
	Area I	Area II
Small Radial Stimulation	35.0	19.1
Large Radial Stimulation	68.0	31.3
Small Vertical Fracture	100.0	32.7
Large Vertical Fracture	282.8	76.4

If a 5-year payoff period is adequate and a wellhead value of $3/Mcf is assumed for the additional gas produced, a large vertical fracture treatment would be desirable in Area I if it cost less than $800,000. Similarly, in Area II, a large radial stimulation would be cost-effective if it could be accomplished for under $100,000.

Table 14 provides the incremental gas recovery over borehole shooting (by area) for each of the stimulation methods.

TABLE 14

INCREMENTAL GAS PRODUCTION OVER BOREHOLE SHOOTING

(Cumulative Recovery, MMcf)

	Small Radial Stimulation r'_w = 30'	Large Radial Stimulation r'_w = 60'	Small Vertical Fracture x_f = 150'	Large Vertical Fracture x_f = 600'	Improvement in Ultimate Recovery: Large Vertical Frac. vs. Borehole Shooting (X-fold)
AREA I					
10 Years	60.4	114.0	160.3	413.6	4.6
40 Years	149.7	264.0	343.4	693.6	2.8
AREA II					
10 Years	33.7	54.3	56.4	125.3	2.9
40 Years	77.8	118.4	120.6	227.9	2.1
AREA III					
10 Years	22.7	37.6	43.0	100.4	3.4
40 Years	44.9	68.8	75.6	138.1	2.1
AREA IV					
10 Years	14.5	25.9	27.9	82.3	4.9
40 Years	48.8	84.8	89.3	240.9	4.0
AREA V					
10 Years	2.8	4.0	3.7	NA	NA
40 Years	8.4	12.2	12.2	NA	NA
AREA VI					
10 Years	2.4	4.3	4.0	12.8	5.9
40 Years	7.9	13.8	12.6	37.2	4.8

G. REVIEW OF TECHNICALLY RECOVERABLE GAS, BY AREA

The analysis showed that the gas flow rates and ultimate recovery per well vary widely in Ohio, from relatively high gas production in the south to low production rates in the shallow, northern area along Lake Erie. The gas potential and production of the six partitioned areas of Ohio are discussed below:

Area I. The southern portion of Ohio, Lawrence and Gallia Counties, contains 543 drillable square miles and an estimated 4.1 Tcf of gas in-place. Because of favorable reservoir properties, such as high pressure, good net thickness and close fracture spacing (5 to 10 feet), gas recoveries per well are high, from 386 MMcf with borehole shooting up to 1,080 MMcf with large vertical fracturing. First year gas production ranges from 36 Mcf/D (borehole shooting) to 238 Mcf/D (large vertical fracturing). Little permeability anisotropy is noted for this area. The major technical concern is being able to contain induced vertical fractures without intersecting water aquifers, particularly in Gallia County.

Area II. The west-central part of Ohio, Licking, Meigs, and other counties, has 3,577 drillable square miles and an estimated 12.4 Tcf of gas in-place. Lower rock pressures and net pay and more widely spaced natural fractures lead to moderate per well recoveries of 206 MMcf (borehole shooting) and 434 MMcf (large vertical fracturing). First year gas production ranges from 19 Mcf/D (borehole shooting) to 68 Mcf/D (large vertical fracturing). High permeability anisotropy (ratio of 6 to 1) and low intersection angle (10^{o}) between the induced and natural fracture systems tend to limit the efficiency of vertically induced fractures. Lower depths, and thus lower drilling costs per well, particularly in the western counties, tend to counterbalance lower gas recoveries.

Area III. The east-central part of Ohio, Gurnsey, Washington, and other counties, has 2,869 drillable acres and an estimated 4.4 Tcf of gas in-place. Small adsorbed gas content, low fracture permeability, and relatively widely spaced natural fractures limit per well recoveries to 127 MMcf (borehole shooting) and 265 MMcf (large vertical fracturing). Moderate permeability anisotropy and a low fracture intersection angle (20^0) limit the effectiveness of vertically induced fractures. Low fracture permeability (0.02 md) and high overburden pressure argue for the use of substantial amounts of proppants with stimulation treatments.

Area IV. The north-central part of Ohio, Wayne, Stark, and other counties, has 2,641 drillable acres and 24.8 Tcf of gas in-place. Stimulation technology appears to be particularly effective in this area, raising per well recoveries from 79 MMcf (borehole shooting) to 320 MMcf with large vertical fracturing. The gas production curve, even though it starts low, 6 Mcf/D (borehole shooting) and 32 Mcf/D (large vertical fracturing), tends to decline little, because of the high adsorbed gas content. Due to low rock pressure, large scale fracturing treatments will need fluids with enhanced clean-up capability and may not be feasible in the northern segment of Area IV.

Areas V and VI. These two smaller areas in the northwest and northeast portions of Ohio, Huron, Trumbull and other counties, have 1,348 drillable square miles and 3.7 Tcf of gas in-place. Per well recoveries are low, at about 50 MMcf per well (with advanced stimulation) as are the initial daily production rates of 1 to 4 Mcf per day. Large vertical fracturing, because of low overburden and rock pressures, is not possible in Area V and may not be possible in Area VI. While these two areas are somewhat similar in gas production, fracture spacing and permeability anisotropy, the setting for the resource base is widely different. Area V has high gas content (200 Mcf/AF), particularly adsorbed gas, but limited net pay. Area VI has low gas content (50 Mcf/AF) with a thick productive interval and very low fracture permeability (0.02 md).

Tables 15 through 26 provide more detailed information on cumulative gas recovery and daily gas production rates, by stimulation method, for the six partitioned areas of Ohio.

TABLE 15

CUMULATIVE GAS RECOVERY BY TYPE OF STIMULATION (MMcf)

(One Well Per 160 Acres)

AREA I

Year	Stimulation Method: Borehole Shooting	Small Radial Stimulation $r'_w = 30'$	Large Radial Stimulation $r'_w = 60'$	Small Vertical Fracture $x_f = 150'$	Large Vertical Fracture $x_f = 600'$
1	13.8	23.4	33.5	46.5	123.4
5	61.3	96.3	129.3	161.3	344.1
10	116.1	176.5	230.1	276.4	529.7
20	216.2	316.2	399.3	463.6	786.8
40	386.4	536.1	650.4	729.8	1,080.0

TABLE 16

AVERAGE DAILY GAS PRODUCTION BY TYPE OF STIMULATION (Mcf/D)

AREA I

Year	Stimulation Method: Borehole Shooting	Small Radial Stimulation $r'_w = 30'$	Large Radial Stimulation $r'_w = 60'$	Small Vertical Fracture $x_f = 150'$	Large Vertical Fracture $x_f = 600'$
1	36	58	80	103	238
5	31	47	60	70	123
10	29	42	52	59	90
20	26	35	47	46	57
40	21	26	29	30	29

TABLE 17

CUMULATIVE GAS RECOVERY BY TYPE OF STIMULATION (MMcf)

(One Well Per 160 Acres)

AREA II

Year	Stimulation Method: Borehole Shooting	Small Radial Stimulation $r'_w = 30'$	Large Radial Stimulation $r'_w = 60'$	Small Vertical Fracture $x_f = 150'$	Large Vertical Fracture $x_f = 600'$
1	7.1	11.4	14.3	14.7	26.1
5	33.7	52.8	65.0	66.4	110.1
10	64.3	98.0	118.6	120.7	189.6
20	118.5	173.3	204.8	207.3	302.1
40	206.0	283.8	324.4	326.6	433.9

TABLE 18

AVERAGE DAILY GAS PRODUCTION BY TYPE OF STIMULATION (Mcf/D)

AREA II

Year	Stimulation Method: Borehole Shooting	Small Radial Stimulation $r'_w = 30'$	Large Radial Stimulation $r'_w = 60'$	Small Vertical Fracture $x_f = 150'$	Large Vertical Fracture $x_f = 600'$
1	19	31	38	39	68
5	18	27	33	33	51
10	16	23	28	28	39
20	14	19	21	21	25
40	10	13	13	13	13

TABLE 19

CUMULATIVE GAS RECOVERY BY TYPE OF STIMULATION (MMcf)

(One Well Per 160 Acres)

AREA III

Year	Stimulation Method				
	Borehole Shooting	Small Radial Stimulation $r'_w = 30'$	Large Radial Stimulation $r'_w = 60'$	Small Vertical Fracture $x_f = 150'$	Large Vertical Fracture $x_f = 600'$
1	5.0	8.8	11.7	13.3	29.8
5	22.3	36.1	45.7	49.6	92.0
10	41.8	64.5	79.4	84.8	142.2
20	75.4	109.9	130.7	137.5	204.6
40	127.2	172.1	196.0	202.8	265.3

TABLE 20

AVERAGE DAILY GAS PRODUCTION BY TYPE OF STIMULATION (Mcf/D)

AREA III

Year	Stimulation Method				
	Borehole Shooting	Small Radial Stimulation $r'_w = 30'$	Large Radial Stimulation $r'_w = 60'$	Small Vertical Fracture $x_f = 150'$	Large Vertical Fracture $x_f = 600'$
1	13	22	29	31	63
5	11	17	21	22	35
10	10	15	17	18	24
20	8	11	12	12	13
40	6	7	7	7	5

TABLE 21

CUMULATIVE GAS RECOVERY BY TYPE OF STIMULATION (MMcf)

(One Well Per 160 Acres)

AREA IV

Year	Stimulation Method				
	Borehole Shooting	Small Radial Stimulation $r'_w = 30'$	Large Radial Stimulation $r'_w = 60'$	Small Vertical Fracture $x_f = 150'$	Large Vertical Fracture $x_f = 600'$
1	2.2	3.8	5.1	5.4	12.2
5	10.7	18.4	24.4	25.6	55.8
10	21.1	35.6	47.0	49.0	103.4
20	41.1	68.1	88.7	92.0	185.5
40	79.1	127.9	163.9	168.4	320.0

TABLE 22

AVERAGE DAILY GAS PRODUCTION BY TYPE OF STIMULATION (Mcf/D)

AREA IV

Year	Stimulation Method				
	Borehole Shooting	Small Radial Stimulation $r'_w = 30'$	Large Radial Stimulation $r'_w = 60'$	Small Vertical Fracture $x_f = 150'$	Large Vertical Fracture $x_f = 600'$
1	6	11	14	15	32
5	6	10	13	13	28
10	6	9	12	12	25
20	5	9	11	11	21
40	5	8	10	10	17

TABLE 23

CUMULATIVE GAS RECOVERY BY TYPE OF STIMULATION (MMcf)

(One Well Per 160 Acres)

AREA V

Year	Stimulation Method			
	Borehole Shooting	Small Radial Stimulation $r'_w = 30'$	Large Radial Stimulation $r'_w = 60'$	Small Vertical Fracture $x_f = 150'$
1	1.2	1.5	1.7	1.6
5	5.6	7.0	7.7	7.5
10	10.8	13.6	14.8	14.5
20	20.8	25.8	28.0	27.5
40	38.8	47.2	51.0	51.0

TABLE 24

AVERAGE DAILY GAS PRODUCTION BY TYPE OF STIMULATION (Mcf/D)

AREA V

Year	Stimulation Method			
	Borehole Shooting	Small Radial Stimulation $r'_w = 30'$	Large Radial Stimulation $r'_w = 60'$	Small Vertical Fracture $x_f = 150'$
1	3	3.8	4.0	4.1
5	3	3.7	4.0	4.0
10	3	3.5	3.8	3.8
20	2.6	3.2	3.5	3.4
40	2.3	2.7	2.9	2.8

TABLE 25

CUMULATIVE GAS RECOVERY BY TYPE OF STIMULATION (MMcf)

(One Well Per 160 Acres)

AREA VI

Year	Stimulation Method: Borehole Shooting	Small Radial Stimulation $r'_w = 30'$	Large Radial Stimulation $r'_w = 60'$	Small Vertical Fracture $x_f = 150'$	Large Vertical Fracture $x_f = 600'$
1	0.3	0.5	0.8	0.7	1.9
5	1.3	2.6	3.6	3.5	8.4
10	2.6	5.0	6.9	6.6	15.4
20	5.1	9.5	12.9	12.3	27.4
40	9.8	17.7	23.6	22.4	47.0

TABLE 26

AVERAGE DAILY GAS PRODUCTION BY TYPE OF STIMULATION (Mcf/D)

AREA VI

Year	Stimulation Method: Borehole Shooting	Small Radial Stimulation $r'_w = 30'$	Large Radial Stimulation $r'_w = 60'$	Small Vertical Fracture $x_f = 150'$	Large Vertical Fracture $x_f = 600'$
1	0.7	1.5	2.0	2.0	4.9
5	0.7	1.4	1.9	1.8	4.2
10	0.7	1.3	1.7	1.7	3.7
20	0.7	1.2	1.6	1.5	3.0
40	0.6	1.1	1.4	1.3	2.5

VII. OTHER FACTORS AFFECTING PRODUCTION

The findings in this study hinge greatly on a series of key assumptions as to geologic characteristics, induced fracture performance, and drainage pattern size and shape. Many of these assumptions are based on theoretical and computer analysis and need to be field verified in practice. To better understand the importance of these assumptions, this section examines the effects on gas recovery of: (1) reduced pattern size; (2) induced fracture behavior at intersection with natural fractures; (3) linkage of wellbore to the natural fracture system; (4) alternative pattern shape, and (5) coproduction with oil-bearing shales.

A. REDUCED PATTERN SIZE

The traditional field development practice is to use a well spacing of 150 to 160 acres, drilled on a square pattern. The analysis shows that, with this spacing, a considerable portion of the gas in-place remains unrecoverable even after 40 years. Today, current practice is to drill on smaller acreage. This analysis therefore examines the recovery efficiencies and feasibility of reducing pattern size to 80 acres per well.

While closer drilling will give a higher overall gas recovery from a given area, the feasibility of drilling on smaller patterns has to be weighed against the expense of the additional well and stimulation. For example, the table below illustrates the effects on cumulative gas production, for the first ten years, of drilling one and two wells on 160 acres in Area I:

Effect of In-Fill Drilling
(10 Year Cumulative Gas Recovery, MMcf)

	160 Acres		Incremental Gas
	1 Well	2 Wells	For Second Well
Borehole Shooting	116	226	110
Large Vertical Fracture	530	941	411

The table above shows that drilling on 80-acre spacing would yield an additional 110 MMcf (over the first 10 years) using borehole shooting, and an additional 411 MMcf (in 10 years), using large vertical fracturing. Tables 27-31 provide this data for selected stimulation techniques (10 year and 40 year recoveries) for each of the six areas.

An overall review of the data indicates that reduced well spacing could be effective in Areas I and IV, marginally effective in Areas II and III, and not effective in Area V. If the low rates of gas production in Area VI can be justified by local gas usage, even closer spacing than 80 acres per well would be preferred.

TABLE 27
SELECTION OF WELL SPACING
AREA I

- Cumulative Gas Production in 10 Years (MMcf)

Stimulation Technique	160-Acre Area 1 Well	160-Acre Area 2 Wells	Incremental Gas For Second Well
Borehole Shooting	116	226	110
Small Radial	177	338	161
Large Radial	230	433	203
Small Vertical Fracture	276	523	247
Large Vertical Fracture	530	941	411

- Cumulative Gas Production in 40 Years (MMcf)

Stimulation Technique	160-Acre Area 1 Well	160-Acre Area 2 Wells	Incremental Gas For Second Well
Borehole Shooting	386	656	270
Small Radial	536	860	324
Large Radial	650	998	348
Small Vertical Fracture	730	1,102	372
Large Vertical Fracture	1,080	1,431	351

TABLE 28
SELECTION OF WELL SPACING
AREA II

- Cumulative Gas Production in 10 Years (MMcf)

	160-Acre Area		Incremental Gas
Stimulation Technique	1 Well	2 Wells	For Second Well
Large Radial Stimulation	119	194	75
Large Vertical Fracture	190	282	92

- Cumulative Gas Production in 40 Years (MMcf)

	160-Acre Area		Incremental Gas
Stimulation Technique	1 Well	2 Wells	For Second Well
Large Radial Stimulation	324	446	122
Large Vertical Fracture	434	538	104

TABLE 29
SELECTION OF WELL SPACING
AREA III

- Cumulative Gas Production in 10 Years (MMcf)

	160-Acre Area		Incremental Gas
Stimulation Technique	1 Well	2 Wells	For Second Well
Large Radial Stimulation	79	138	59
Large Vertical Fracture	142	224	82

- Cumulative Gas Production in 40 Years (MMcf)

	160-Acre Area		Incremental Gas
Stimulation Technique	1 Well	2 Wells	For Second Well
Large Radial Stimulation	196	266	70
Large Vertical Fracture	265	316	51

TABLE 30
SELECTION OF WELL SPACING
AREA IV

- Cumulative Gas Production in 10 Years (MMcf)

Stimulation Technique	160-Acre Area 1 Well	160-Acre Area 2 Wells	Incremental Gas For Second Well
Large Radial Stimulation	47	92	45
Large Vertical Fracture	103	202	99

- Cumulative Gas Production in 40 Years (MMcf)

Stimulation Technique	160-Acre Area 1 Well	160-Acre Area 2 Wells	Incremental Gas For Second Well
Large Radial Stimulation	164	312	148
Large Vertical Fracture	320	586	266

TABLE 31
SELECTION OF WELL SPACING
AREA V AND VI

- Cumulative Gas Production in 10 Years (MMcf)

Stimulation Technique	160-Acre Area 1 Well	160-Acre Area 2 Wells	Incremental Gas For Second Well
Large Radial Stimulation			
Area V	15	18	3
Area VI	7	14	7

- Cumulative Gas Production in 40 Years (MMcf)

Stimulation Technique	160-Acre Area 1 Well	160-Acre Area 2 Wells	Incremental Gas For Second Well
Large Radial Stimulation			
Area V	51	60	9
Area VI	24	46	22

B. ALTERNATIVE INDUCED FRACTURE BEHAVIOR AT NATURAL FRACTURE INTERSECTIONS

The analysis assumes that an induced fracture will enter and propagate along the same path as the natural fracture system. However, two other possibilities could occur:

- The induced fracture could enter the natural fracture system and terminate due to energy dissipation at the interface; or,
- The induced fracture could cross the natural fracture system for the full fracture design length.

These three alternatives are shown schematically on Exhibit 18.

1. Low Fracture Intersection Angle

In areas having a low induced fracture intersection angle (with the natural fracture system), it appears to make little difference whether the fracture parallels or crosses the natural fracture system. However, with a large scale stimulation (a 600-foot induced fracture) substantial improvement in gas recovery results when the induced fracture parallels (providing a well propped, highly conductive flow path) rather than terminates in the first natural fracture system encountered.

The table below indicates the results of this analysis in Area II, which has a fracture intersection angle of 10 degrees.

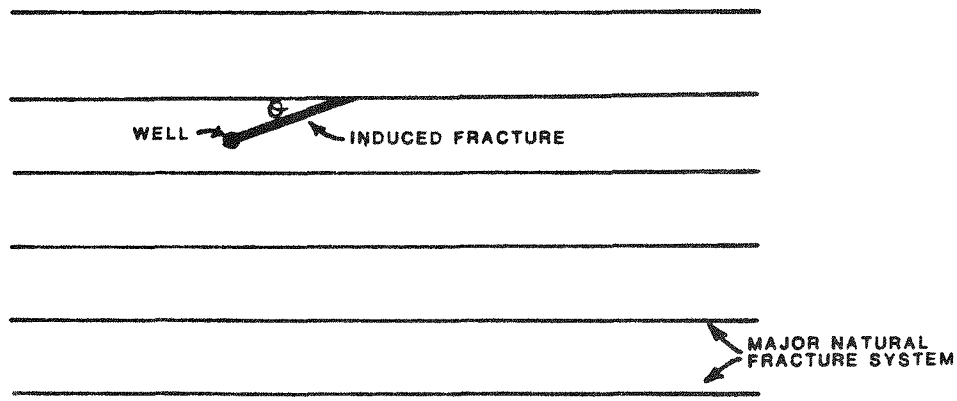
Effect of Alternative Induced Fracture Performance
Low Angle Case (Cumulative Recovery, MMcf)

Stimulation Technique	Terminates In Natural Frac System	Parallels Natural Frac System	Crosses Natural Frac System
Small Vertical Fracture (x_f=150')			
10 Years	97	121	127
40 Years	281	327	337
Large Vertical Fracture (x_f=600')			
10 Years	97	190	198
40 Years	281	434	444

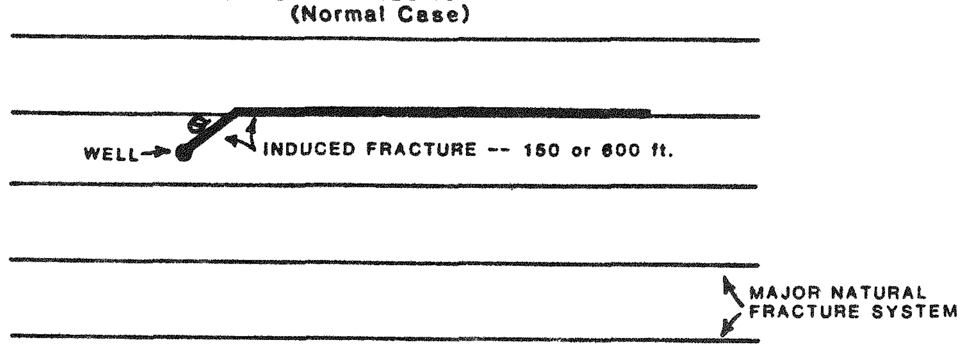
Exhibit 18

UNDERSTANDING OF INDUCED FRACTURE PROPAGATION

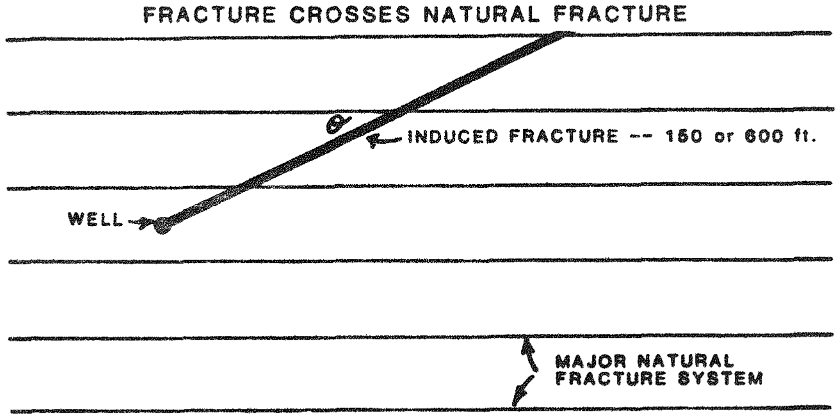
FRACTURE ARRESTED AT INTERSECTION WITH NATURAL FRACTURE



FRACTURE PROPAGATES ALONG NATURAL FRACTURE (Normal Case)



FRACTURE CROSSES NATURAL FRACTURE



For Area II, crossing the natural fracture system results in only a small (3 percent) increase in gas recovery for both the small and large vertical fracture cases. However, should the induced fracture merely terminate in the natural fracture system, gas recovery could be severely reduced--by 20 percent for the small, 150-foot vertical fracture case, and by 50 percent for the large, 600-foot vertical fracture case.

2. High Fracture Intersection Angle

At higher fracture intersection angles such as 40 degrees, the positive effects of crossing a natural fracture system become evident. In this type of setting, the induced fracture presents a high permeability surface area partially orthogonal to the direction of greater natural permeability.

The reservoir properties of Area IV, which has a 40 degree intersection angle and a permeability anisotropy ratio of 6:1, are used to examine the effect of fracture intersection angle.

	Effect of Induced Alternative Fracture Performance High Angle Case (Cumulative Recovery, MMcf)	
Stimulation Technique	Parallels Natural Frac System	Crosses Natural Frac System
Small Vertical Fracture (x_f=150')		
10 Years	49	74
40 Years	168	243
Large Vertical Fracture (x_f=600')		
10 Years	103	159
40 Years	320	461

In this area, crossing the natural fracture system increases gas recovery by 40 to 50 percent over the case where the induced fracture merely parallels the natural fracture system.

3. Induced Fracture Perpendicular to Natural Fracture System

Although the highest intersection angle for any area in Ohio is 40 degrees, it may be possible in localized areas for the induced fracture to be normal, at 90 degrees to the natural fracture system.

To examine the maximum effect of fracture intersection angle, the reservoir properties of Area II were used for the Base Case. For the alternative case, the same reservoir properties were used, except that the intersection angle was set at 90^{0}, and to accommodate the 600-foot vertical fracture perpendicular in the 3 by 1 rectangle it was necessary to extend the drainage area to 320 acres. The increased gas recovery is shown below:

Effect of Alternative Induced Fracture Performance
Maximum Angle Case (Cumulative Recovery, MMcf)

Stimulation Well With Large Vertical Fracture	Parallels Natural Frac System (160 Acres/Well Angle 10^{o})	Crosses Natural Frac System (320 Acres/Well Angle 90^{o})
(x_f=600')		
10 Years	190	339
40 Years	434	796

In this alternative case, ultimate gas recovery increases by nearly 80 percent in the first ten years and offers the promise, should such technology be able to be developed, of unlocking the gas reserves in otherwise marginally productive areas of the Devonian shale.

C. NON-INTERSECTION OF NATURAL FRACTURE SYSTEM

The analysis shows that the gas recovery and initial production rate will be decreased greatly even if only a small "skin" effect remains between the extended wellbore and the natural fracture system.

The sensitivity case assumes a wellbore in the center of a widely-spaced, natural fracture system, as displayed in Exhibit 19. In this case, where the distance from the natural fracture system to the edge of the stimulated area is only five feet, and the matrix permeability is low, 10^{-5} md (as used in this study), there is virtually no gas production. As Exhibit 20 shows, the permeability in the shale matrix must exceed 0.01 md to have attractive gas flow rates when the stimulation method fails to fully contact the natural fracture system.

D. ALTERNATIVE PATTERN SHAPE

A preliminary analysis indicated that a rectangular drainage pattern is more efficient in recovering gas than a square pattern in anisotropic permeability regions. However, this elongated drilling pattern may not always be possible due to existing wells or other constraints in the area.

This sensitivity analysis examines the cumulative gas recovery for three stimulation technologies (borehole shooting, a large radial stimulation, and a large vertical fracture) over three drainage shapes (a square, a 3 by 1 rectangle, and a 6 by 1 rectangle), for Area II which exhibits a permeability anisotropy ratio of 6:1 and a fracture intersection angle of 10 degrees.

The analysis shows that when borehole shooting is used for well stimulation, the drainage shape has little impact on gas recovery, Table 32. However, for the other two stimulation techniques, recovery efficiency is improved by 5 to 10 percent by using alternatives to the traditional square pattern. The analysis shows that the most efficient drainage shape is a rectangle of about 3 by 1, although the optimum dimensions will depend

Exhibit 19

ILLUSTRATION OF MATRIX SKIN
FOR WIDELY SPACED NATURAL FRACTURES

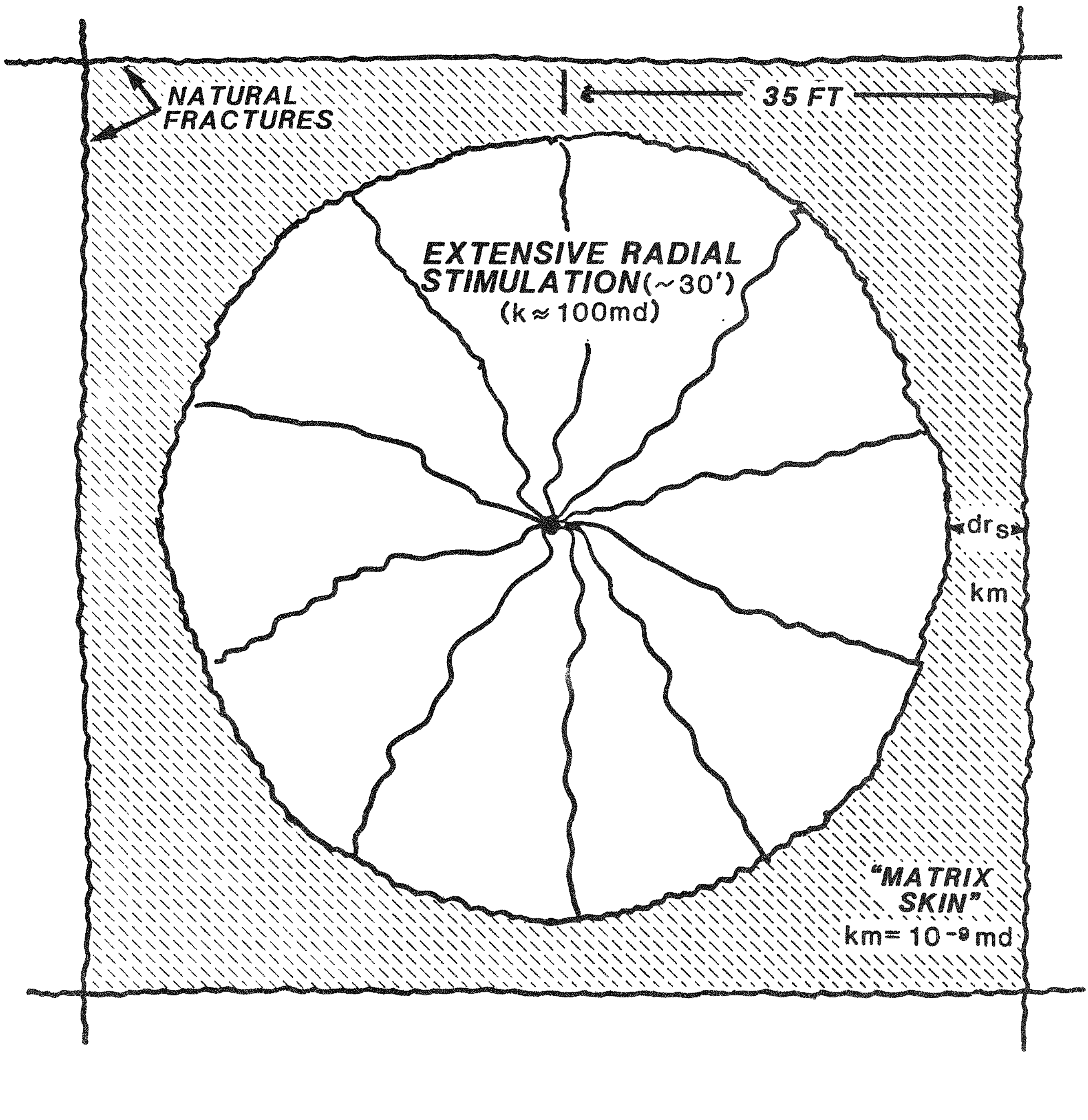
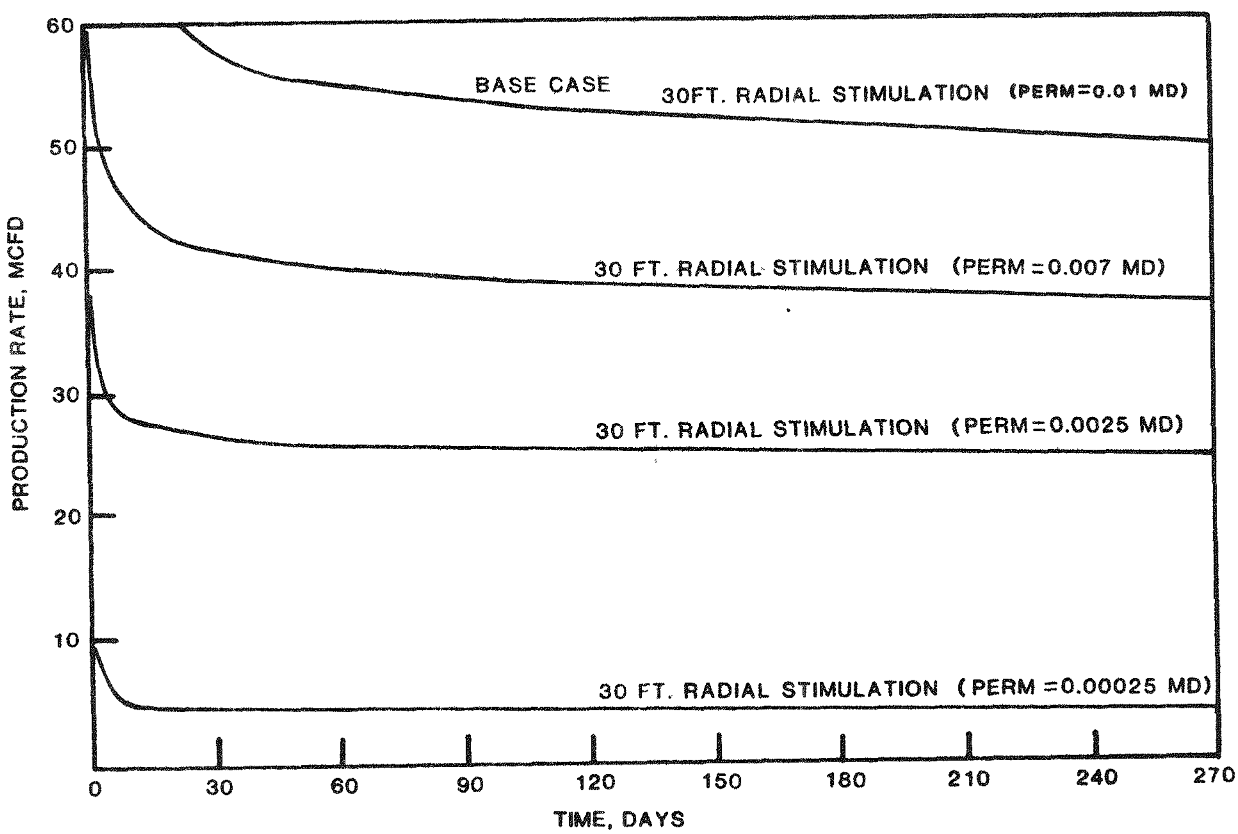


Exhibit 20

MATRIX SKIN VERSUS PRODUCTION



upon the stimulation technique used, drainage pattern size, and the permeability anisotropy in the region. Further study is required to determine the most optimal drainage pattern shape under the large variety of geological variables and well stimulation practices present for the Devonian shale.

TABLE 32
SELECTION OF DRAINAGE PATTERN SHAPE
AREA II

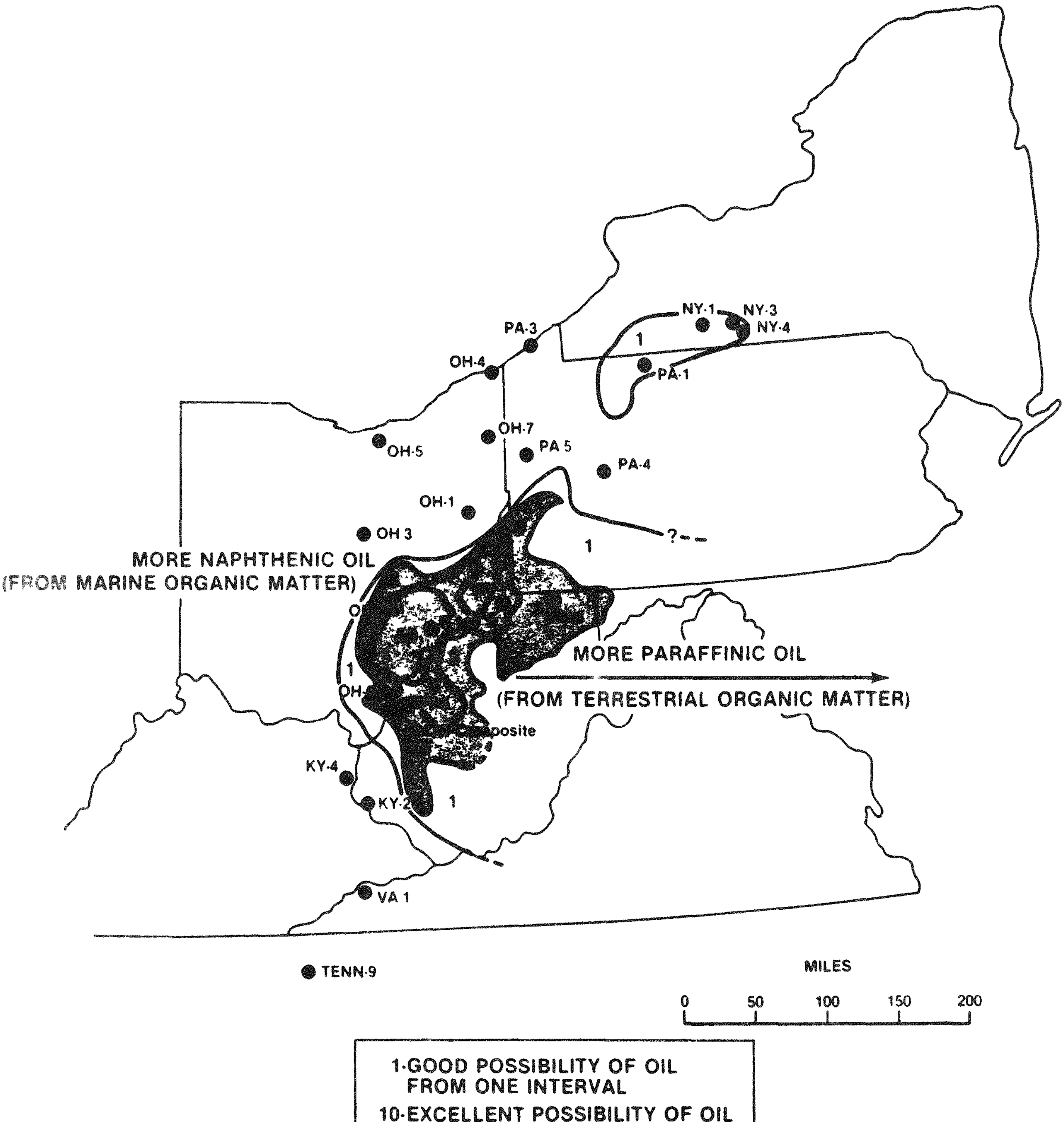
Stimulation Technique	Cumulative Gas Recovery From Alternative Patterns: Square Pattern (MMcf)	3x1 Pattern (MMcf)	6x1 Pattern (MMcf)
Borehole Shooting			
10 Years	63	63	63
40 Years	206	206	206
Large Radial Stimulation (r_w=60')			
10 Years	113	119	114
40 Years	309	324	311
Large Vertical Fracture (x_f=600')			
10 Years	172	190	180
40 Years	402	434	414

E. COPRODUCTION WITH OIL BEARING SHALES

In several areas, some intervals within the Upper Devonian have been considered as a potential source of oil. Recent drilling has resulted in several wells initially producing high volumes of oil. The coproduction of oil with gas from the Devonian could result in wells paying out in less than a year. In these instances a much smaller drilling pattern, on the order of 40 acres, may be justified. Potential oil producing areas are shown on Exhibit 21 reproduced from the Mound Report.

Exhibit 21

OVERALL OIL SOURCE ROCK POTENTIAL



APPALACHIAN BASIN STUDY AREA

REFERENCES

1. Resource and Exploration Assessment of the Oil and Gas Potential in the Devonian Gas Shales of the Appalachian Basin (Mound Lab) 1982 (DOE/DP/0053-1125.

2. Analysis of Devonian Shales in the Appalachian Basin (Cliffs Minerals) 1982 (DOE/MC/14693-352,353).

3. Modeling of Devonian Shale Gas Reservoir Performance (SAI) 1979 (DOE/MC/08216-1354).

4. Fractured Shale Gas Reservoir Performance Study--An Offset Well Interference Field Test (DOE/METC) 1982 (SPE 11224).

5. Analyses of Devonian Shale Multiwell Interference Tests in Meigs Co., Ohio (SAI) 1982 (DOE/MC/16283-1155).

6. SPE Symposium on Low Permeability Reservoirs, Experimental Evaluation of Fracturing Fluid Interaction With Tight Reservoir Rocks and Propped Fractures (Terra Tek) 1979.

7. Stress Ratio/Structure Map of the Appalachian Basin (METC) 1981 (DOE/METC).

8. Hydraulic Fracturing Experiments in Devonian Shale and Pre-Fractured Hydrostone (SAI) 1981 (DOE/MC/08216-1331).

9. Comparative Analysis of Stimulations in the Eastern Gas Shales (METC) 1981 (DOE/METC-145)

10. Well Test Analysis for Devonian Shale Wells (University of Tulsa) 1981 (DOE/MCV/14645).

11. Unconventional Gas Sources-Vol. III, Devonian Shale (National Petroleum Council) 1980.

APPENDIX A

DATA LOCATIONS

DATA SOURCES

NUMBER OF RECORDS BY TOWNSHIP

	Long-Term Production LTP	Initial Production IP	Rock Pressure RP	IP/RP	ALL	TOTAL
ASHLAND COUNTY						
Sullivan	0	0	1	0	0	1
ASHTABULA COUNTY						
Geneva	0	1	1	0	0	2
Saybrook	0	3	0	0	0	3
ATHENS COUNTY						
Carthage	0	2	1	0	0	3
Lodi	0	3	0	0	0	3
BELMONT COUNTY						
Richland	0	1	0	0	0	1
Somerset	0	1	0	0	0	1
CARROLL COUNTY						
Augusta	0	2	0	0	0	2
COLUMBIANA COUNTY						
Franklin	0	1	1	0	0	2
CUYAHOGA COUNTY						
Middleburg	1	0	0	0	0	1
GALLIA COUNTY						
Harrison	0	7	0	0	0	7
HOCKING COUNTY						
Ward	0	0	1	0	0	1

NUMBER OF RECORDS BY TOWNSHIP (Cont.)

	Long-Term Production LTP	Initial Production IP	Rock Pressure RP	IP/RP	ALL	TOTAL
JACKSON COUNTY						
Jackson	0	0	1	0	0	1
Milton	0	0	1	0	0	1
KNOX COUNTY						
Clinton	0	3	1	0	0	4
LAWRENCE COUNTY						
Elizabeth	0	0	1	0	0	1
Fayette	1	0	0	0	0	1
Lawrence	1	0	0	0	0	1
Perry	1	0	1	0	0	2
Rome	0	0	4	0	4	8
Union	0	0	6	0	22	28
Upper	0	1	0	0	0	1
Windsor	1	0	21	0	3	25
LICKING COUNTY						
Bennington	0	0	0	1	0	1
Franklin	0	2	0	0	0	2
Granville	0	0	1	0	0	1
Hanover	0	0	1	0	0	1
Licking	2	3	1	2	0	8
Madison	0	0	1	0	0	1
Newark	7	0	3	4	0	14
Newton	16	0	21	13	0	50
Washington	0	0	1	1	0	2
LORAIN COUNTY						
Avon	0	0	1	0	0	1
Columbia	0	1	0	2	0	3
Elyria	0	0	1	0	0	1
Grafton	0	0	1	0	0	1
Henrietta	0	1	1	1	0	3
Pittsfield	0	0	1	0	0	1
Ridgeville	0	0	1	0	0	1

NUMBER OF RECORDS BY TOWNSHIP (Cont.)

	Long-Term Production LTP	Initial Production IP	Rock Pressure RP	IP/RP	ALL	TOTAL
MEDINA COUNTY						
Granger	7	0	0	0	0	7
Hinckley	3	0	1	0	0	4
Liverpool	0	0	2	0	0	2
MEIGS COUNTY						
Chester	12	0	1	2	6	21
Lebanon	0	2	1	1	0	4
Olive	5	0	2	1	1	9
Orange	0	1	14	0	0	15
Salisburg	0	1	0	0	0	1
Sutton	2	3	1	0	1	7
MONROE COUNTY						
Benton	0	4	0	0	0	4
Bethel	0	1	0	0	0	1
Center	0	1	0	0	0	1
Jackson	0	1	0	0	0	1
Malaga	0	3	1	0	0	4
Perry	7	1	0	0	0	8
Seneca	0	1	0	0	0	1
Washington	0	5	1	1	0	7
MORGAN COUNTY						
Deerfield	1	0	0	0	0	1
MUSKINGUM COUNTY						
Brush Creek	1	0	0	0	0	1
NOBLE COUNTY						
Elk	0	14	3	0	0	17
Enoch	0	8	0	0	0	8

NUMBER OF RECORDS BY TOWNSHIP (Cont.)

	Long-Term Production LTP	Initial Production IP	Rock Pressure RP	IP/RP	ALL	TOTAL
PERRY COUNTY						
Monroe	1	0	0	0	0	1
RICHLAND COUNTY						
Holmes	1	0	0	0	0	1
Jackson	0	0	2	0	0	2
Washington	0	0	2	0	0	2
SUMMIT COUNTY						
Twinsburg	0	0	3	0	0	3
TRUMBULL COUNTY						
Athens	1	11	0	0	0	12
TUSCARAWAS COUNTY						
Mill	0	0	1	0	0	1
VINTON COUNTY						
Elk	0	0	2	0	0	2
WASHINGTON COUNTY						
Belpre	0	3	1	0	0	4
Decatur	0	1	0	0	0	1
Durham	0	1	0	0	0	1
Fearing	0	0	1	0	0	1
Grandview	0	16	1	0	0	17
Independence	0	6	0	0	0	6
Lawrence	0	5	0	0	0	5
Liberty	0	7	0	0	0	7
Ludlow	0	9	1	0	0	10
Marietta	0	3	0	0	0	3
Newport	0	12	1	0	0	13
Salem	0	1	0	0	0	1
Warren	0	3	0	0	0	3

APPENDIX B

EGSP CORE WELL DESCRIPTIONS AND LOCATIONS

DETAILED DESCRIPTION OF EGSP APPALACHIAN BASIN CORE WELL LOCATIONS

No.	Mound Well	Well Name	State	County
1	7239	Kentucky-West Virginia Gas Co./ Nicholas Combs #7239	Kentucky	Perry
2	KY-2	Columbia Gas Transmission Corp./ Columbia Gas #20336	Kentucky	Martin
3	KY-4	Ashland Oil Co./ Skaggs-Kelley Unit #3-RS	Kentucky	Johnson
4	NY-1	National Fuel Gas Supply Corp./ # 5213 (Jo) EGSP NY # 1	New York	Allegany
5	NY-3	Arlington Exploration Co./ Ambrose Scudder Unit No. 1	New York	Steuben
6	NY-4	Arlington Exploration Co./ Valley Vista View, Inc. #1	New York	Steuben
7	NY-5	Gustavson & Associates	New York	Steuben
8	OH-1	Canton Oil & Gas Co./ Glen-Gery #5-74S	Ohio	Carroll
9	R-109	River Gas Company/ Florence L. House #R-109 (OH-2)	Ohio	Washington

DETAILED DESCRIPTION OF EGSP APPALACHIAN BASIN CORE WELL LOCATIONS

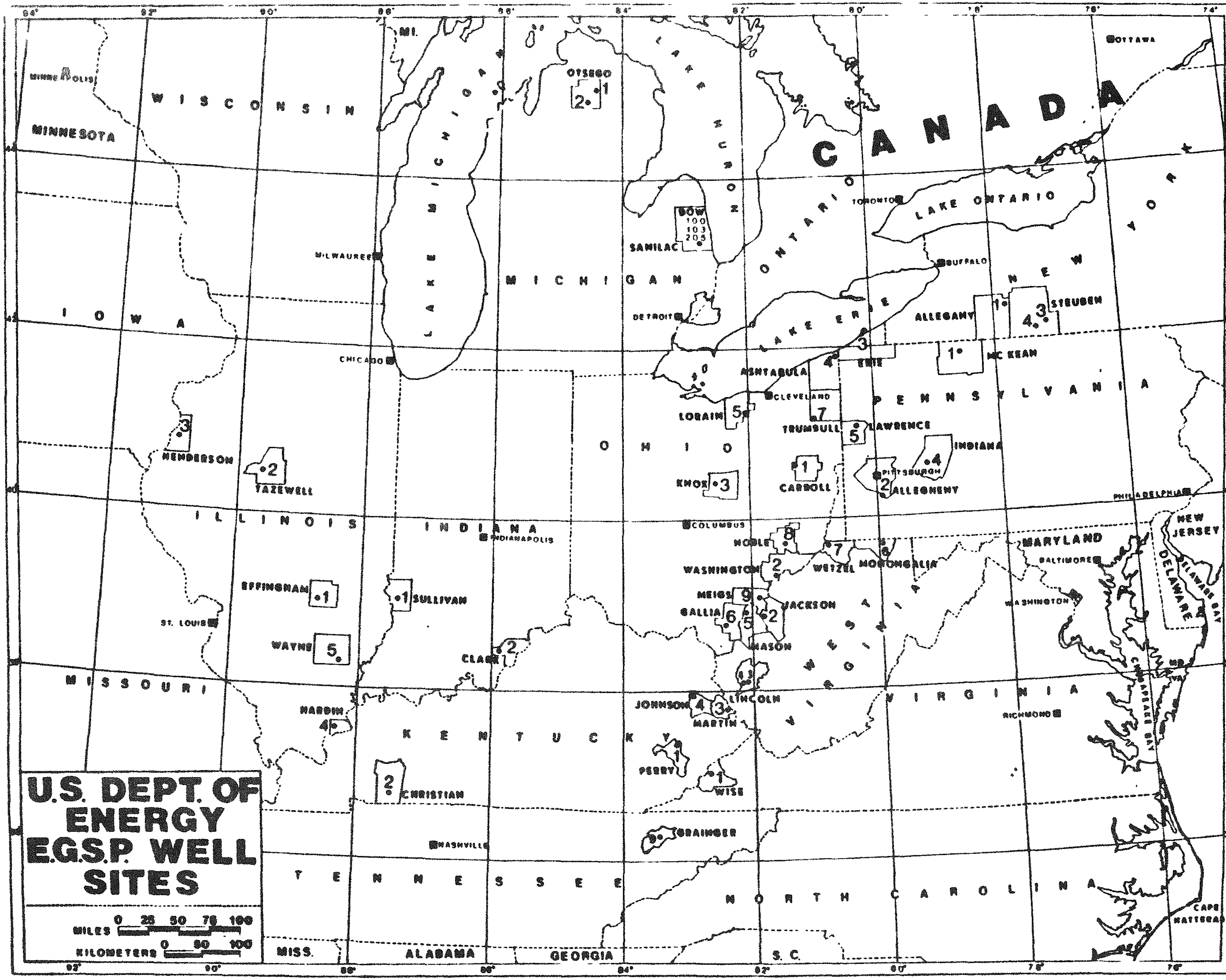
No.	Mound Well	Well Name	State	County
10	OH-3	Thurlow Weed & Associates/ Louise Beckholt #1	Ohio	Knox
11	OH-4	Mansanto Research Corp./Bessemer and Lake Erie Railroad Co. #3	Ohio	Ashtabula
12	OH-5	Columbia Gas Transmission Corp./ D.M. Wakefield #10148-7	Ohio	Lorain
13	OH-6-1	Mitchell Energy Corp./#1-5 Carpenter	Ohio	Gallia
14	OH-6-2	Mitchell Energy Corp.	Ohio	Gallia
15	OH-6-3	Mitchell Energy Corp./L. McCombs #1-6	Ohio	Gallia
16	OH-6-4	Mitchell Energy Corp./#1-8 straight	Ohio	Gallia
17	OH-6-5	Mitchell Energy Corp./ Carter #1-9	Ohio	Gallia
18	OH-7	Columbia Gas Transmission Corp./ Anna Meleski #20143	Ohio	Trumbull
19	OH-8	Donohue, Austey & Morrill/ Schockling # 1	Ohio	Noble

DETAILED DESCRIPTION OF EGSP APPALACHIAN BASIN CORE WELL LOCATIONS

No.	Mound Well	Well Name	State	County
20	OH-9	Gruy Federal, Inc./DOE/Columbia Gas Co. #10056-A	Ohio	Meigs
21	PA-1	Minard Run Oil Co./ Minard Run Exploration #1	Pennsylvania	McKean
22	PA-2	C.E. Power Systems/ C.E. Power Systems #1	Pennsylvania	Allegheny
23	PA-3	Monsanto Research Corp. Pennsylvania DER/Presque Isle State Park #1	Pennsylvania	Erie
24	PA-4	Gruy Federal, Inc./DOE/Glen McCall #5	Pennsylvania	Indiana
25	PA-5	Peoples Natural Gas/C. Sokevitz # 1	Pennsylvania	Lawrence
26	TENN-9	Gruy Federal, Inc./DOE/ Gruy Federal #1	Tennessee	Grainger
27	VA-1	Columbia Gas Transmission Corp./ Penn Va. Corp. Farm Well #20338	Virginia	Wise
28	11940	Consolidated Gas Supply Corp./ L.A. Bales #11940	West Virginia	Jackson

DETAILED DESCRIPTION OF EGSP APPALACHIAN BASIN CORE WELL LOCATIONS

No.	Mound Well	Well Name	State	County
29	WV-5	Reel Drilling Co./ D/K Farm #3	West Virginia	Mason
30	WV-6	U.S. Dept of Energy MERC #1	West Virginia	Monongalia
31	WV-7	Mobay Chemical Corp./ H. Emch & A. Pyles Unit #1	West Virginia	Wetzel



U.S. DEPT. OF ENERGY E.G.S.P. WELL SITES
MILES 0 25 50 75 100
KILOMETERS 0 50 100
CANADA
WISCONSIN
MINNESOTA
IOWA
ILLINOIS
INDIANA
MICHIGAN
OHIO
PENNSYLVANIA
NEW YORK
NEW JERSEY
DELAWARE
MARYLAND
WEST VIRGINIA
VIRGINIA
KENTUCKY
TENNESSEE
NORTH CAROLINA
MISSOURI
MISS.
ALABAMA
GEORGIA
S. C.
MI.
LAKE MICHIGAN
LAKE HURON
LAKE ERIE
LAKE ONTARIO
ONTARIO
DELAWARE BAY
CHESAPEAKE BAY
CAPE HATTERAS
MINNEAPOLIS
MILWAUKEE
CHICAGO
DETROIT
TORONTO
BUFFALO
OTTAWA
CLEVELAND
PITTSBURGH
COLUMBUS
INDIANAPOLIS
ST. LOUIS
PHILADELPHIA
BALTIMORE
WASHINGTON
RICHMOND
NASHVILLE
OTSEGO
SANILAC
BOW 100 103 205
ALLEGANY
STEUBEN
MC KEAN
ERIE
ASHTABULA
LORAIN
TRUMBULL
LAWRENCE
INDIANA
ALLEGHENY
CARROLL
KNOX
NOBLE
WASHINGTON
WETZEL
MONONGALIA
MEIGS
GALLIA
JACKSON
MASON
LINCOLN
JOHNSON
MARTIN
PERRY
WISE
GRAINGER
HENDERSON
TAZEWELL
EFFINGHAM
WAYNE
SULLIVAN
CLARK
HARDIN
CHRISTIAN

APPENDIX C

REPRESENTATIVE WELL SELECTION METHODOLOGY

REPRESENTATIVE WELL SELECTION METHODOLOGY

Representative wells were identified for those counties where sufficient production data were available to characterize the resource in a statistically meaningful way.

Selection of Representative Wells. The first phase in selecting representative wells was to screen the data base and refine it using the following approach:

- The wells were individually metered.
- Production from shale members was distinguished from other producing horizons.
- High, average and low producers were included.
- Production data for a minimum of four weeks had to be available for a county to be included in the selection process.

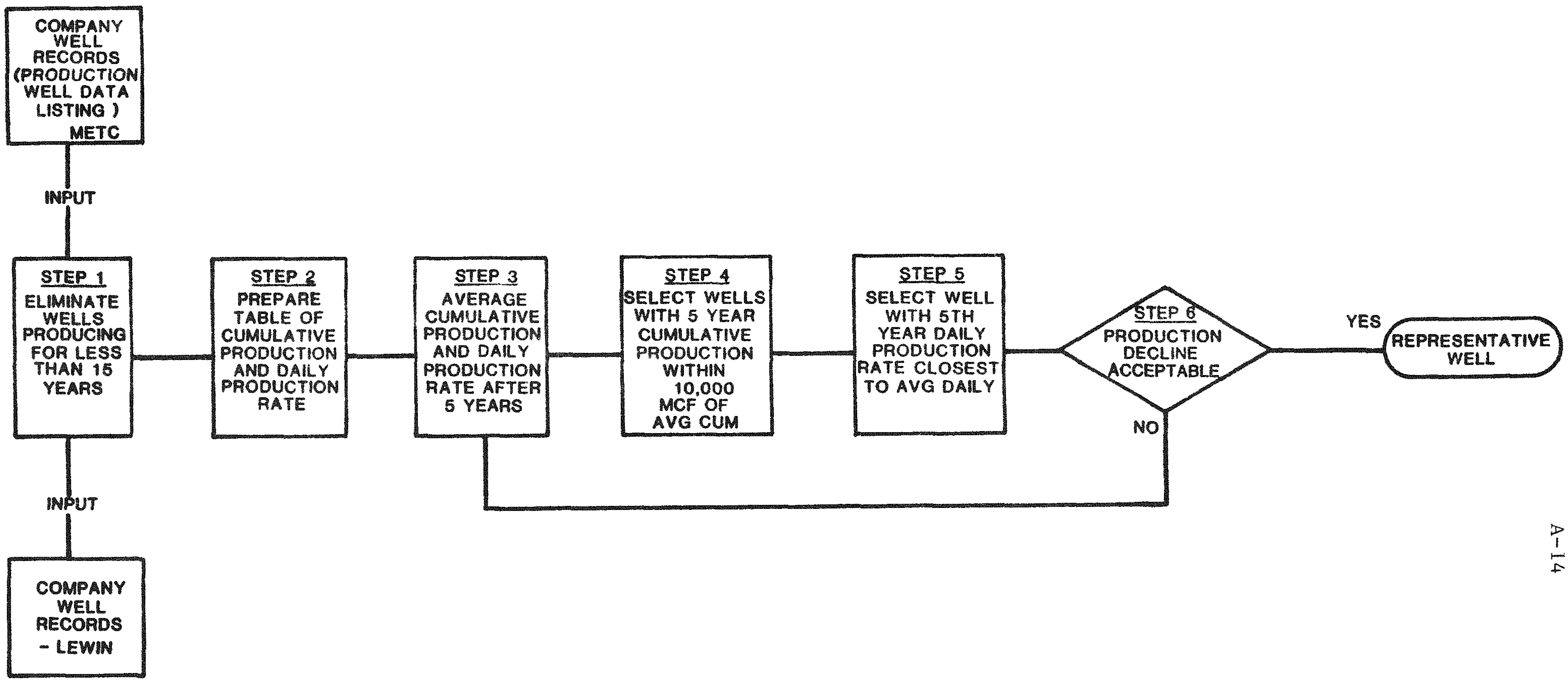
The purpose of this screening was to ensure that the well records were representative and adequate to characterize the resource.

This procedure limited the counties with long-term well data to three: Lawrence, Licking, and Meigs.

The second phase of the selection process to identify representative wells for each county used the process outlined on the following Exhibit. The steps for this process are discussed in detail below:

Step 1: To properly assess shale production, the wells used for history matching must have produced for at least 15 years. Wells producing for less than 15 years were eliminated from the selection set.

PROCESS FOR SELECTING REPRESENTATIVE WELLS



<u>Step 2</u>: A production table by well was prepared for each county. This table consisted of identifying the daily production rate for the well during its fifth full year on line along with cumulative production. If a well did not produce for a complete year initially, the initial production was not utilized in establishing the daily rate (Mcf/D) for the fifth year of production. In addition, the cumulative production (MMcf) was adjusted to reflect the elimination of the initial production figure.

<u>Step 3</u>: Using the data generated in Step 2, the average cumulative production and average daily production rate after five years were computed for each of these Ohio counties.

<u>Step 4</u>: Wells which have a five-year cumulative production within ± 10,000 MCF of the average computed in Step 2 were selected as representative wells.

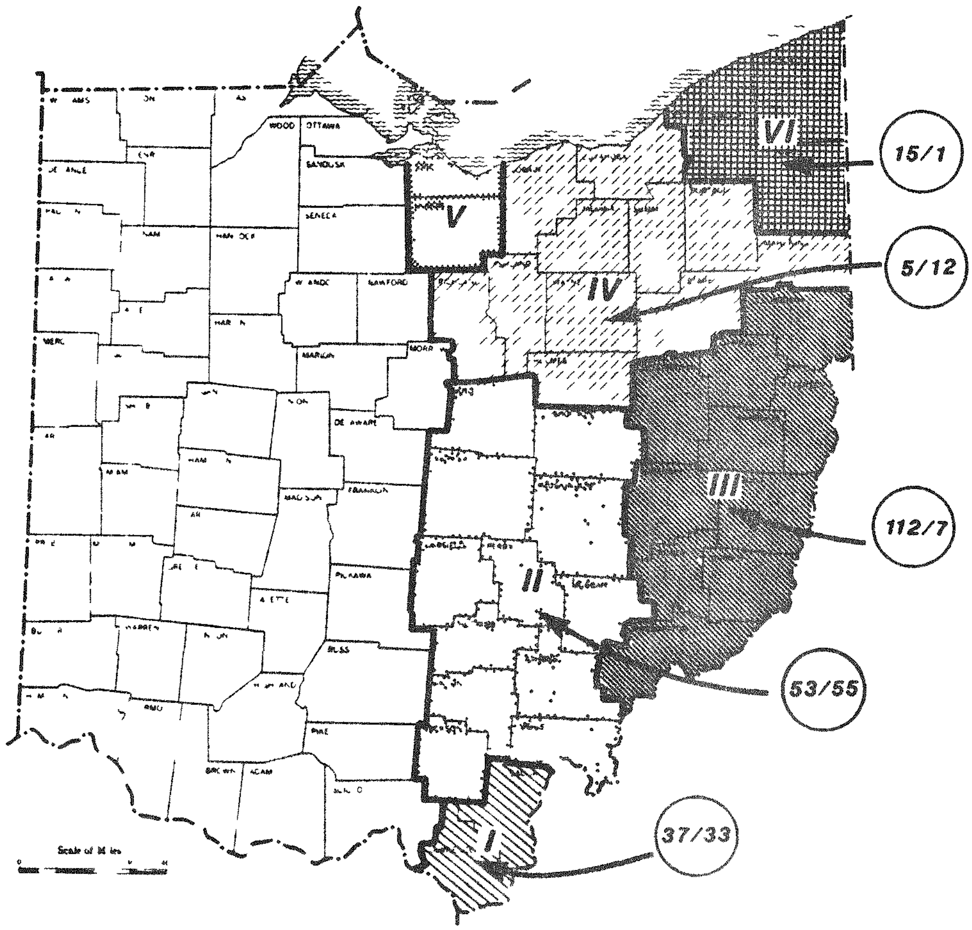
<u>Step 5</u>: Using the candidate wells identified in Step 3, the well which has a fifth year daily production rate closest to the average computed in Step 2 was selected as the best candidate well.

<u>Step 6</u>: The well identified in the last step was reviewed for production decline. This step constitutes a "test of acceptability." If the production decline was abnormal, the well was eliminated from consideration and the process returned to Step 3. If the production decline was acceptable, the well was selected as the "representative well" for that county.

APPENDIX D

PRODUCTION DATA REFERENCE

PRIMARY PARTITIONED AREAS
DEVONIAN GAS SHALES OF OHIO



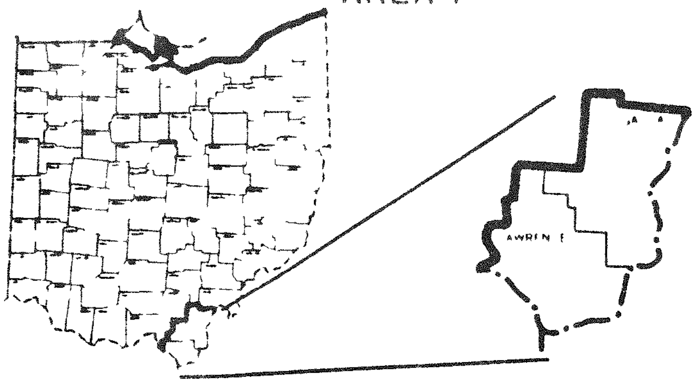
#/ NUMBER OF OPEN-FLOW GAS PRODUCTION RECORDS
/# NUMBER OF LONG-TERM GAS PRODUCTION RECORDS

AVERAGE GEOLOGIC PROPERTIES BY AREA

PARTITIONED AREA	FRACTURE SPACING (feet)	PERMEABILITY ANISOTROPY (ratio)	INTERSECTION ANGLE (degrees)
I	10	1 1	N/A
II	20	6 1	10
III	20	4 1	20
IV	20	6 1	40
V	20	8 1	40
VI	20	8 1	40

SUMMARY OF OHIO DEVONIAN SHALE GAS POTENTIAL

AREA I



BASIC DATA

KEY RESERVOIR PROPERTIES

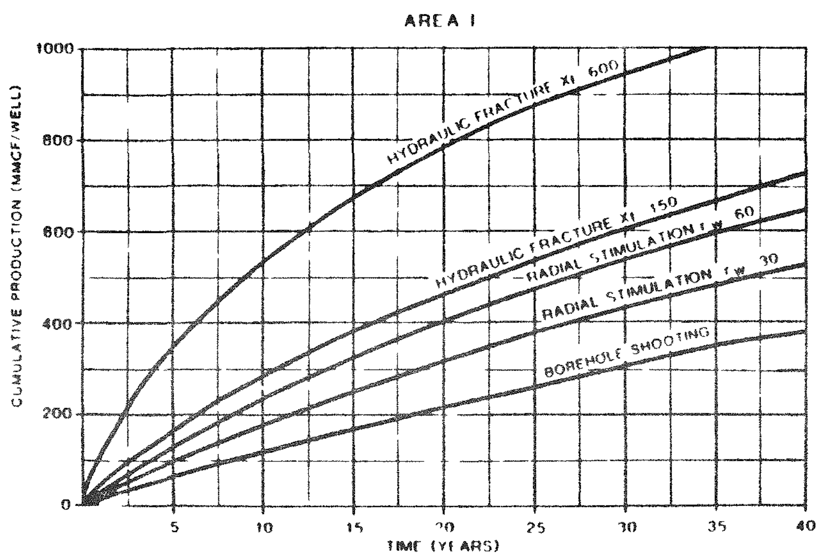
• DEPTH (ft)	2320
• ROCK PRESSURE (psig)	690
• GAS CONTENT (Mcf/AF)	100
• "NET" THICKNESS (ft)	119
• FRACTURE PERM (md)	0276
• INIT OPEN FLOW (Mcf/D)	49
• PERM ANISOTROPY (ratio)	1 1
• FRACTURE INTERSECTION ANGLE (°)	N/A
• FRACTURE SPACING (ft)	10

GAS POTENTIAL

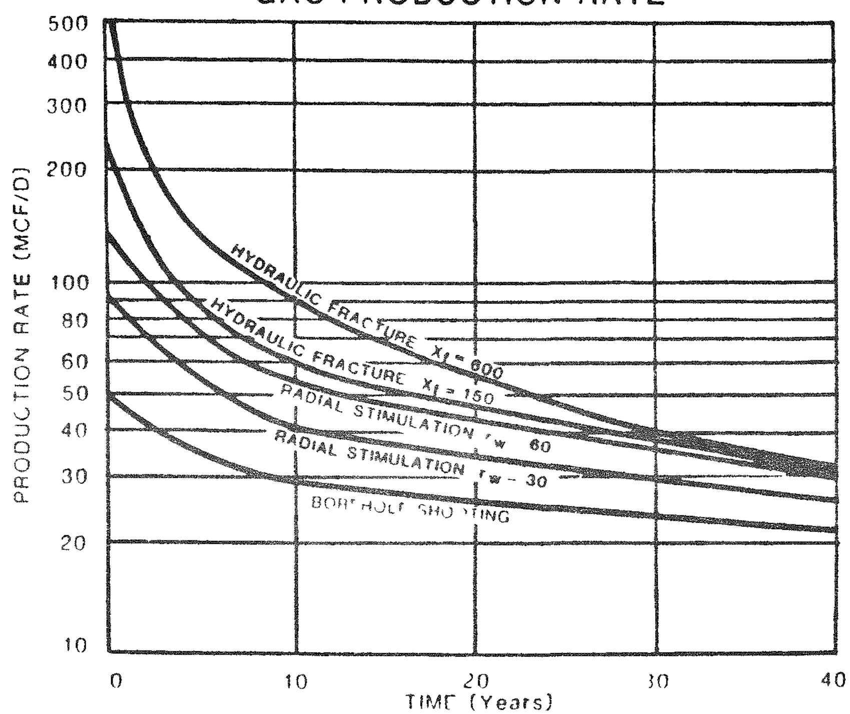
• DRILLABLE AREA (ACRES)	347,520
• RECOVERABLE GAS w/ BOREHOLE SHOOTING (BCF)	839

STIMULATION TECHNOLOGY	CUMULATIVE RECOVERY (MMCF/WELL) 10 YRS	40 YRS
• BOREHOLE SHOOTING	116	386
• RADIAL STIMULATION		
rw-30	176	536
-- rw-60'	230	650
• VERTICAL FRACTURE		
- xf-150'	276	730
-- xf-600'	530	1,080

CUMULATIVE GAS RECOVERY



GAS PRODUCTION RATE



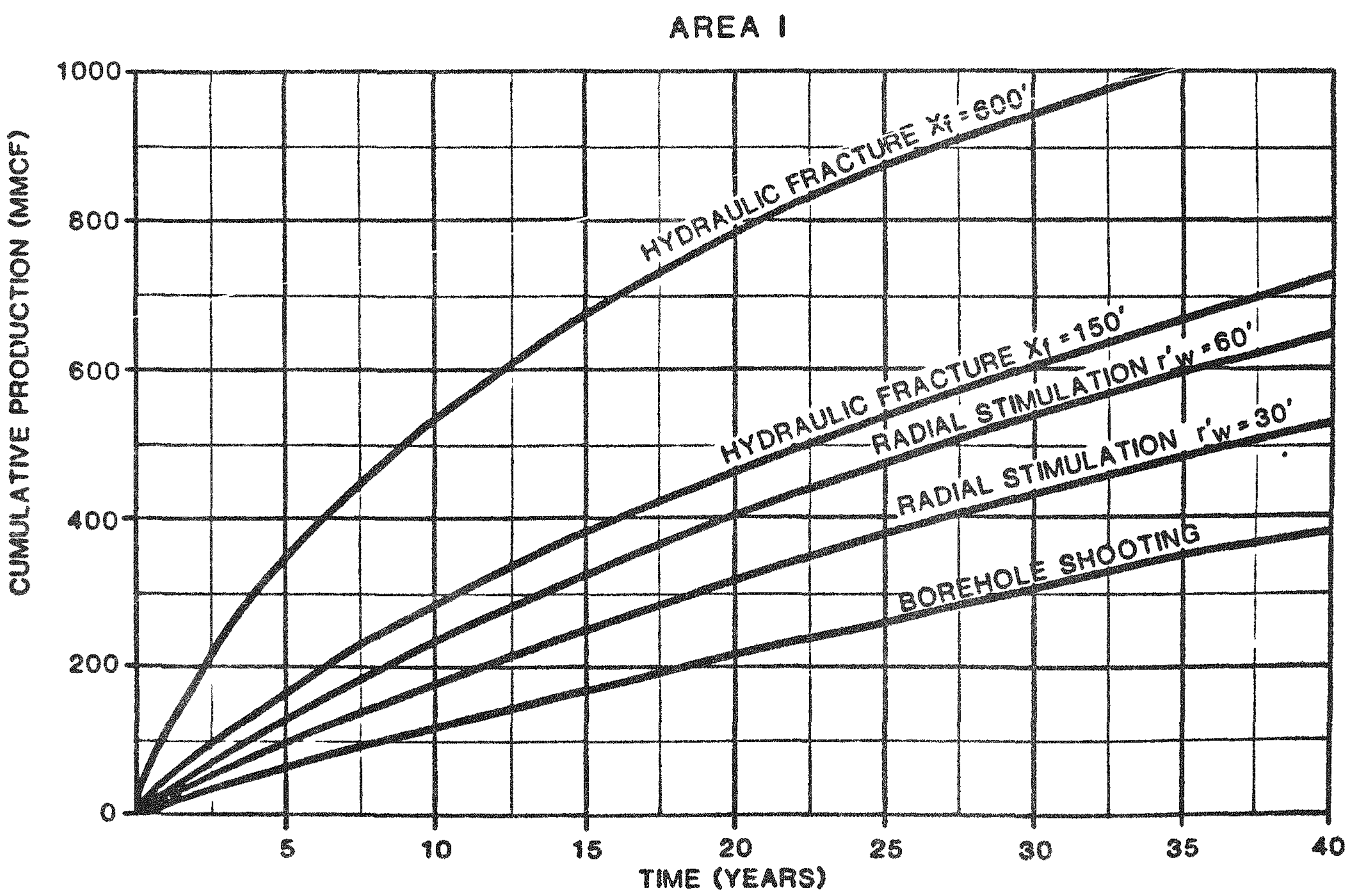
CUMULATIVE GAS RECOVERY BY TYPE OF STIMULATION (MMcf)

(One Well Per 160 Acres)

AREA I

Year	Borehole Shooting	Small Radial Stimulation r'w = 30'	Large Radial Stimulation r'w = 60'	Small Vertical Fracture xf = 150'	Large Vertical Fracture xf = 600'
1	13.8	23.4	33.5	46.5	123.4
5	61.3	96.3	129.3	161.3	344.1
10	116.1	176.5	230.1	276.4	529.7
20	216.2	316.2	399.3	463.6	786.8
40	386.4	536.1	650.4	729.8	1,080.0

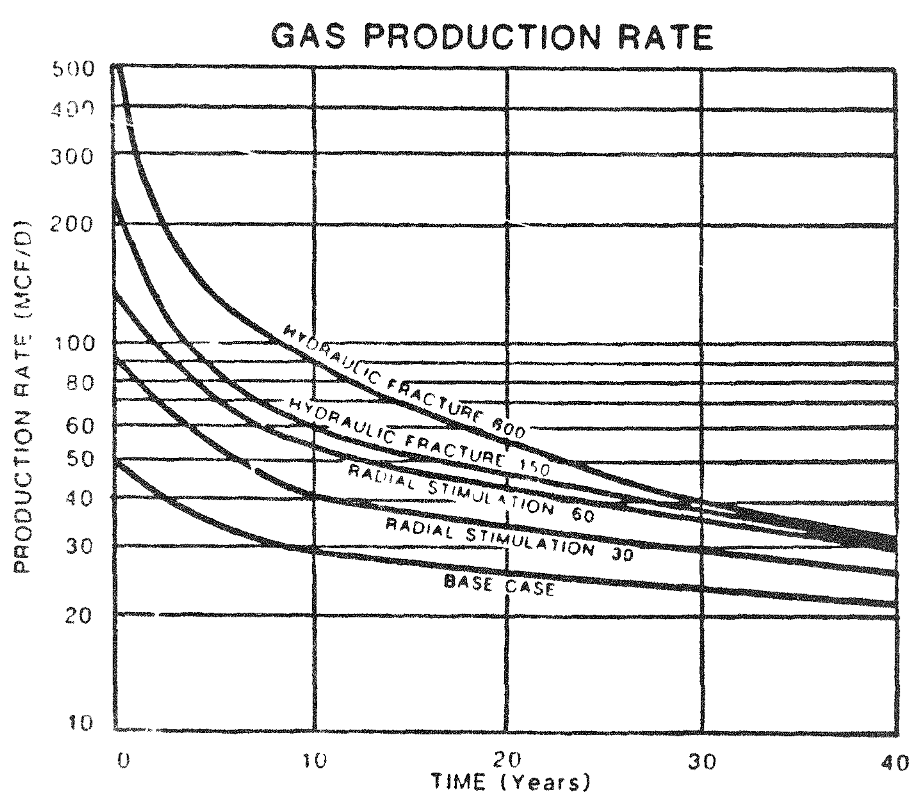
(The header "Stimulation Method" spans the five method columns.)



AVERAGE DAILY GAS PRODUCTION BY TYPE OF STIMULATION (Mcf/d)

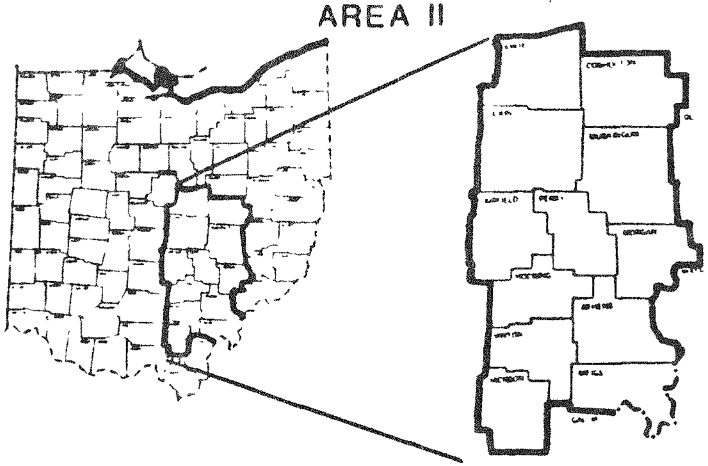
AREA I

	Stimulation Method				
Year	Borehole Shooting	Small Radial Stimulation r'_w=30'	Large Radial Stimulation r'_w=60'	Small Vertical Fracture x_f=150'	Large Vertical Fracture x_f=600'
1	36	58	80	103	238
5	31	47	60	70	123
10	29	42	52	59	90
20	26	35	47	46	57
40	21	26	29	30	29



SUMMARY OF OHIO DEVONIAN SHALE GAS POTENTIAL

AREA II



BASIC DATA

KEY RESERVOIR PROPERTIES

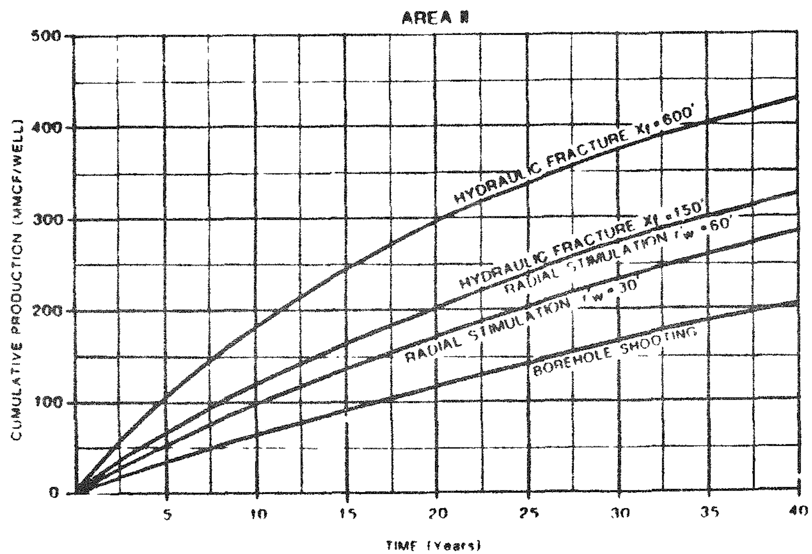
• DEPTH (ft)	1500
• ROCK PRESSURE (psig)	240
• GAS CONTENT (Mcf/AF)	90
• "NET" THICKNESS (ft)	60
• FRACTURE PERM (md)	2993
• INIT. OPEN FLOW (Mcf/D)	25
• PERM. ANISOTROPY (ratio)	6:1
• FRACTURE INTERSECTION ANGLE (°)	10
• FRACTURE SPACING (ft)	20

GAS POTENTIAL

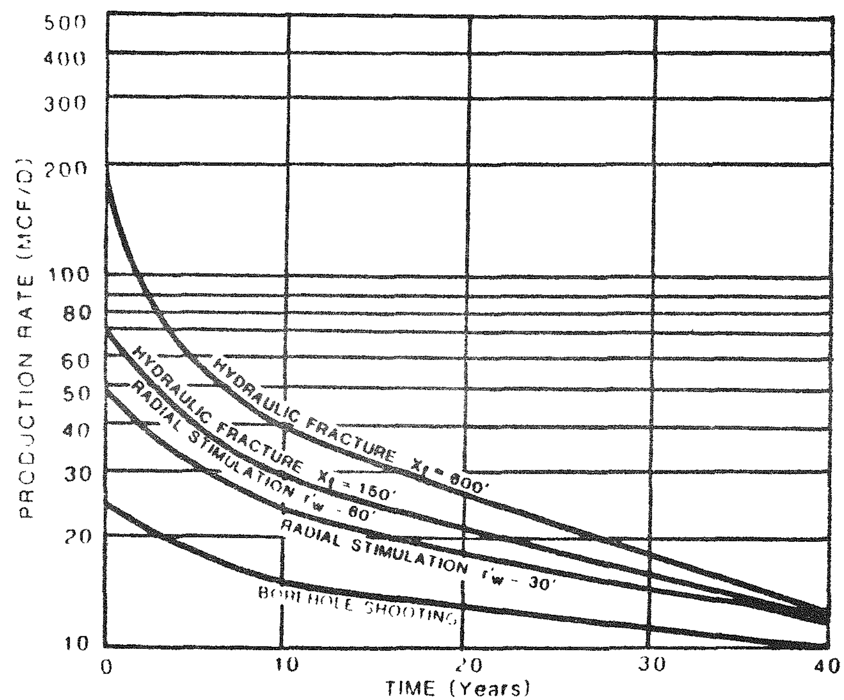
• DRILLABLE AREA (ACRES)	2,289,280
• RECOVERABLE GAS w/BOREHOLE SHOOTING (BCF)	2,947

STIMULATION TECHNOLOGY	CUMULATIVE RECOVERY (MMCF/WELL) 10 YRS	40 YRS
• BOREHOLE SHOOTING	64	206
• RADIAL STIMULATION		
-- rw-30'	98	284
-- rw-60'	119	324
• VERTICAL FRACTURE		
-- xf-150'	121	327
-- xf-600'	190	434

CUMULATIVE GAS RECOVERY



GAS PRODUCTION RATE

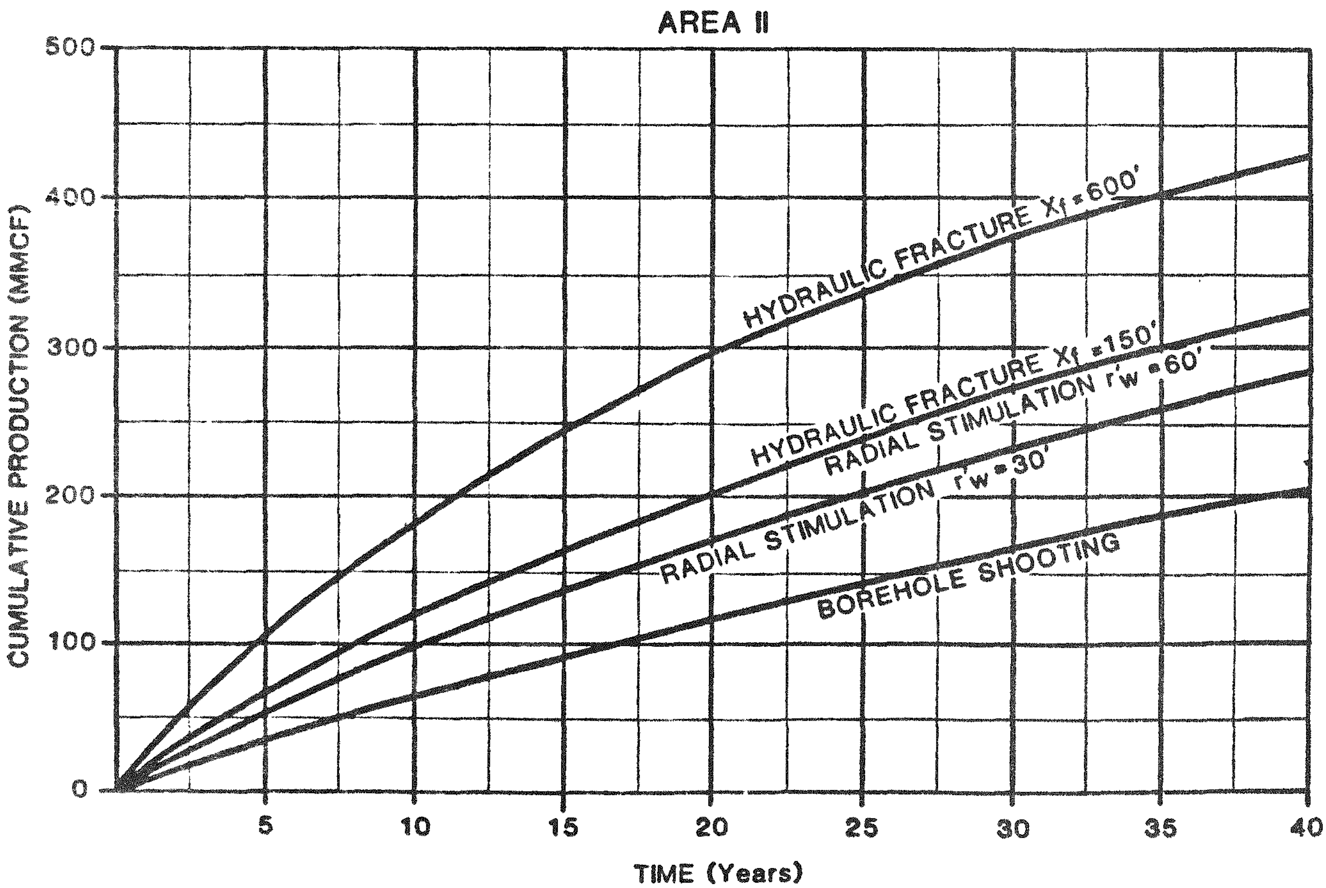


CUMULATIVE GAS RECOVERY BY TYPE OF STIMULATION (MMcf)

(One Well Per 160 Acres)

AREA II

	Stimulation Method				
Year	Borehole Shooting	Small Radial Stimulation $r'_w = 30'$	Large Radial Stimulation $r'_w = 60'$	Small Vertical Fracture $x_f = 150'$	Large Vertical Fracture $x_f = 600'$
1	7.1	11.4	14.3	14.7	26.1
5	33.7	52.8	65.0	66.4	110.1
10	64.3	98.0	118.6	120.7	189.6
20	118.5	173.3	204.8	207.3	302.1
40	206.0	283.8	324.4	326.6	433.9

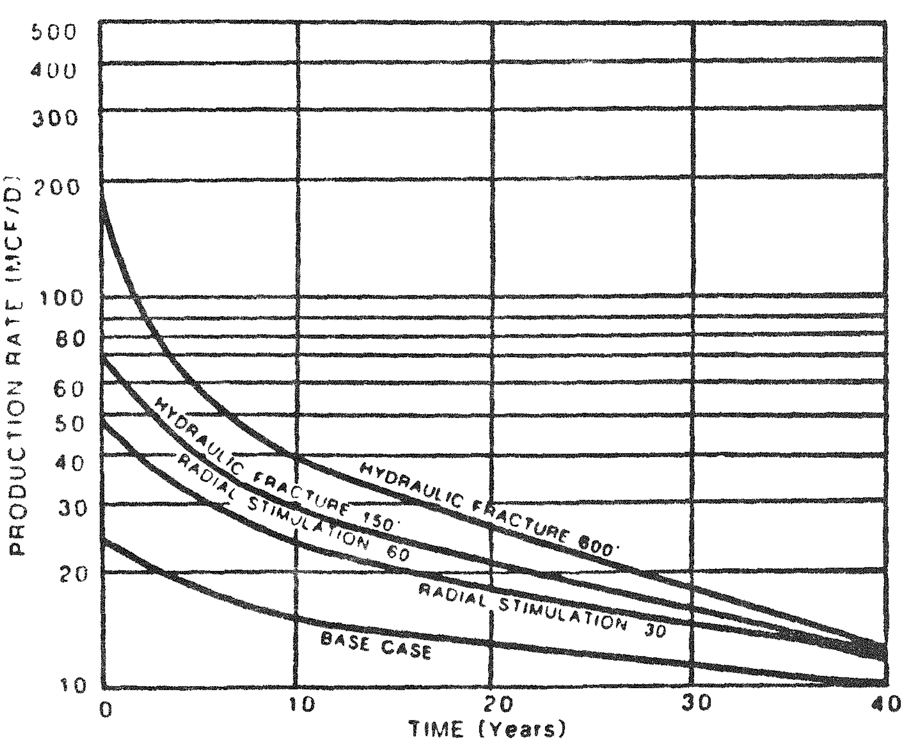


AVERAGE DAILY GAS PRODUCTION BY TYPE OF STIMULATION (Mcf/d)

AREA II

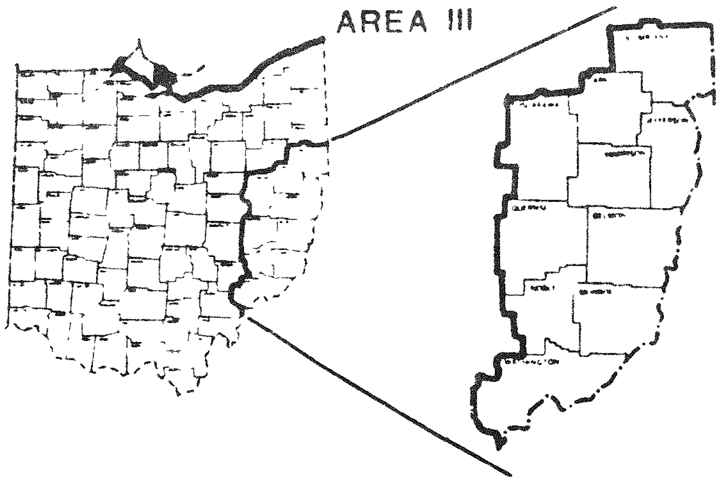
	Stimulation Method				
Year	Borehole Shooting	Small Radial Stimulation r'_w=30'	Large Radial Stimulation r'_w=60'	Small Vertical Fracture x_f=150'	Large Vertical Fracture x_f=600'
1	19	31	38	39	68
5	18	27	33	33	51
10	16	23	28	28	39
20	14	19	21	21	25
40	10	13	13	13	13

GAS PRODUCTION RATE



SUMMARY OF OHIO DEVONIAN SHALE GAS POTENTIAL

AREA III



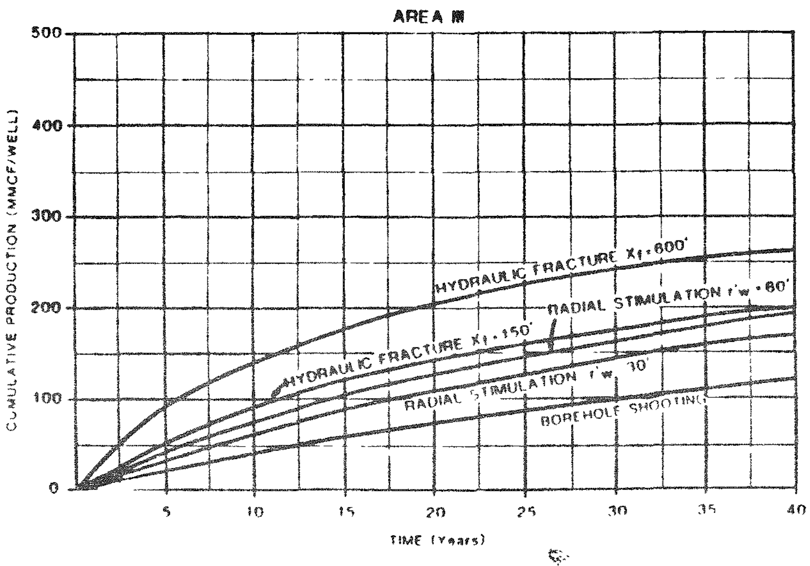
BASIC DATA

KEY RESERVOIR PROPERTIES	
• DEPTH (ft)	3560
• ROCK PRESSURE (psig)	625
• GAS CONTENT (Mcf/AF)	20
• "NET" THICKNESS (ft)	120
• FRACTURE PERM (md)	02
• INIT. OPEN FLOW (Mcf/D)	19
• PERM. ANISOTROPY (ratio)	4:1
• FRACTURE INTERSECTION ANGLE (°)	20
• FRACTURE SPACING (ft)	20

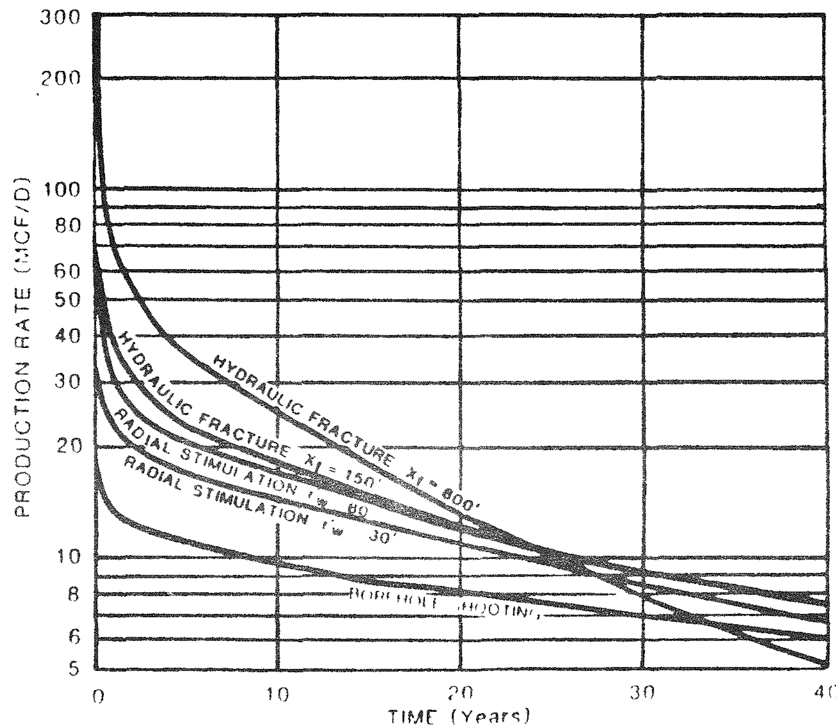
GAS POTENTIAL	
• DRILLABLE AREA (ACRES)	1,836,000
• RECOVERABLE GAS w/BOREHOLE SHOOTING (BCF)	1,459

STIMULATION TECHNOLOGY	CUMULATIVE RECOVERY (MMCF/WELL) 10 YRS	40 YRS
• BOREHOLE SHOOTING	42	127
• RADIAL STIMULATION		
-- r'w-30'	64	172
-- r'w-60'	79	196
• VERTICAL FRACTURE		
-- Xf-150'	85	203
-- Xf-600'	142	265

CUMULATIVE GAS RECOVERY



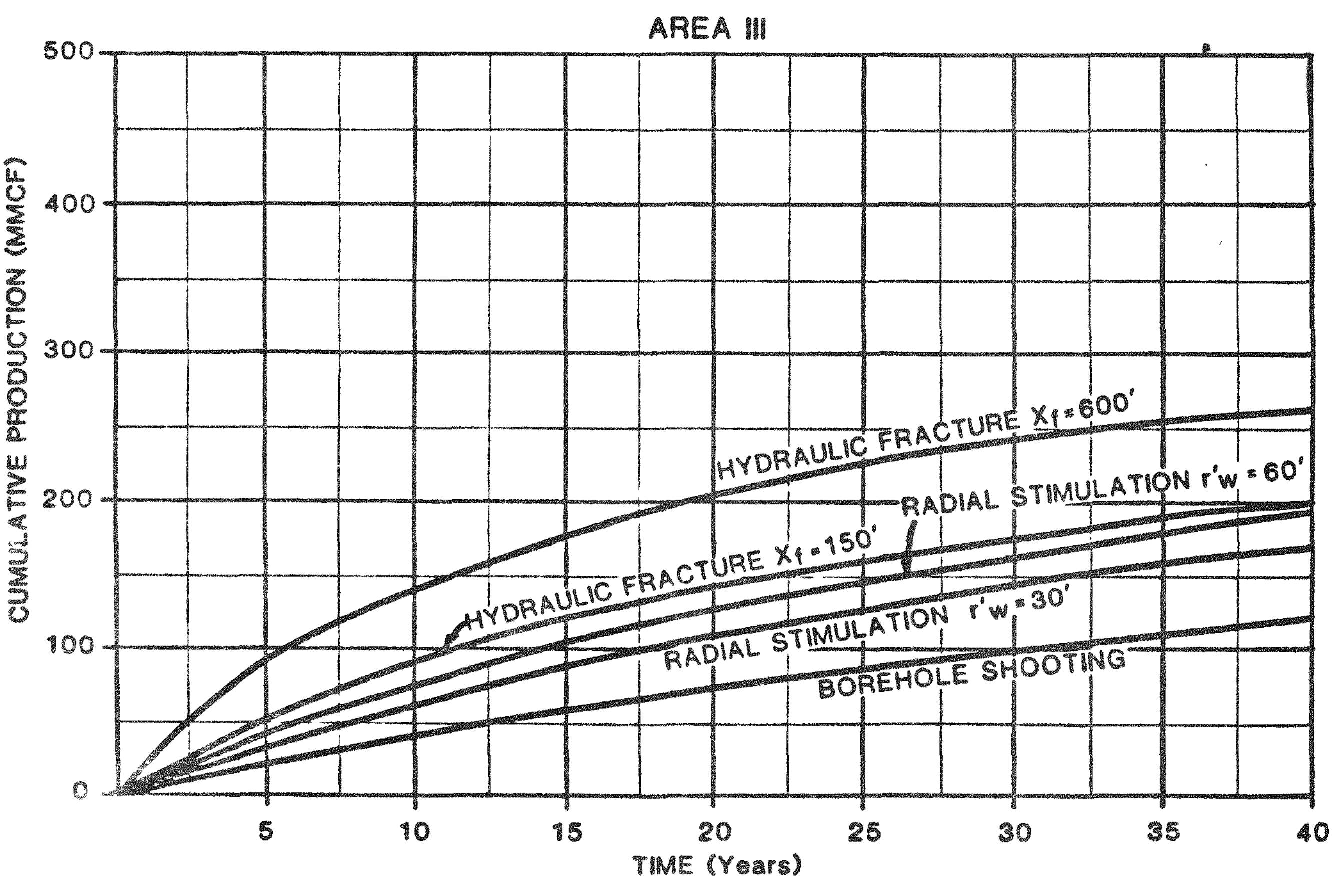
GAS PRODUCTION RATE



CUMULATIVE GAS RECOVERY BY TYPE OF STIMULATION (MMcf)
(One Well Per 160 Acres)

AREA III

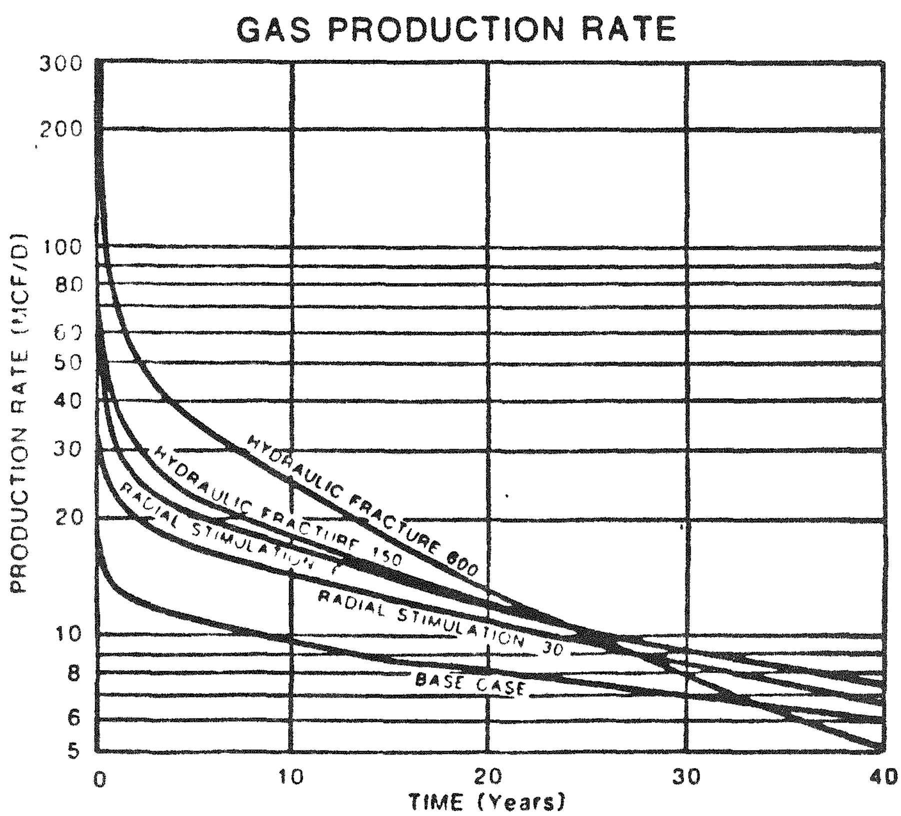
Year	Borehole Shooting	Small Radial Stimulation $r'_w = 30'$	Large Radial Stimulation $r'_w = 60'$	Small Vertical Fracture $x_f = 150'$	Large Vertical Fracture $x_f = 600'$
1	5.0	8.8	11.7	13.3	29.8
5	22.3	36.1	45.7	49.6	92.0
10	41.8	64.5	79.4	84.8	142.2
20	75.4	109.9	130.7	137.5	204.6
40	127.2	172.1	196.0	202.8	265.3



AVERAGE DAILY GAS PRODUCTION BY TYPE OF STIMULATION (Mcf/d)

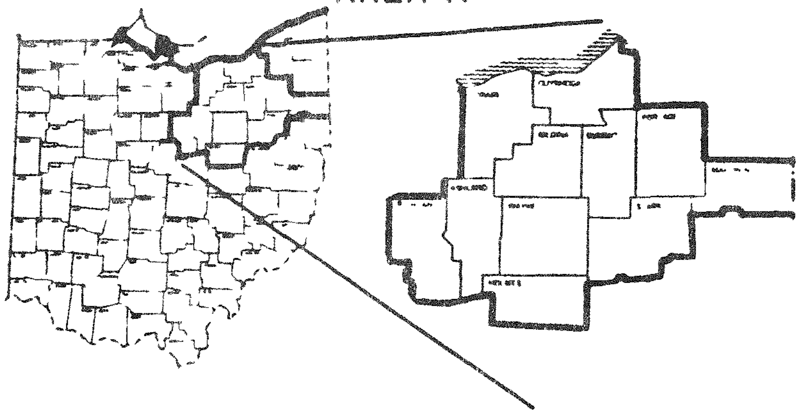
AREA III

Year	Borehole Shooting	Small Radial Stimulation r'_w=30'	Large Radial Stimulation r'_w=60'	Small Vertical Fracture x_f=150'	Large Vertical Fracture x_f=600'
	Stimulation Method				
1	13	22	29	31	63
5	11	17	21	22	35
10	10	15	17	18	24
20	8	11	12	12	13
40	6	7	7	7	5



SUMMARY OF OHIO DEVONIAN SHALE GAS POTENTIAL

AREA IV



BASIC DATA

KEY RESERVOIR PROPERTIES

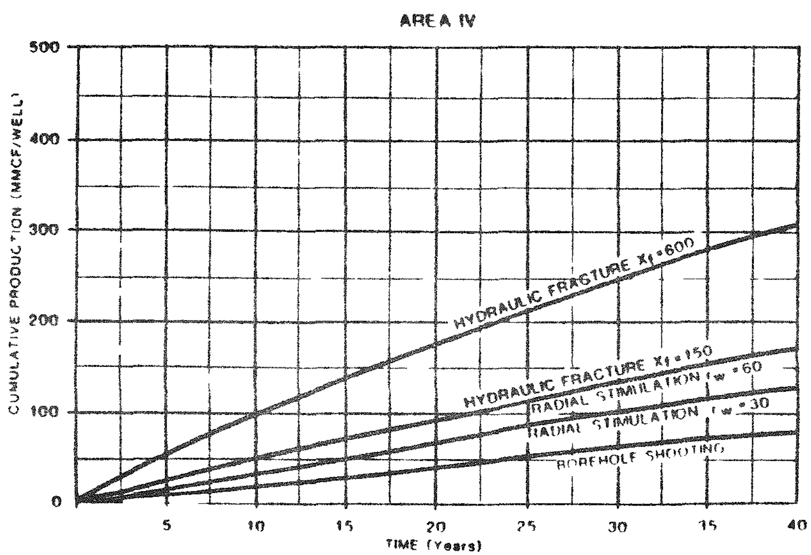
• DEPTH (ft)	1860
• ROCK PRESSURE (psig)	215
• GAS CONTENT (Mcf/AF)	140
• "NET" THICKNESS (ft)	105
• FRACTURE PERM (md)	0674
• INIT OPEN FLOW (Mcf/D)	8
• PERM ANISOTROPY (ratio)	6 1
• FRACTURE INTERSECTION ANGLE (°)	40
• FRACTURE SPACING (ft)	20

GAS POTENTIAL

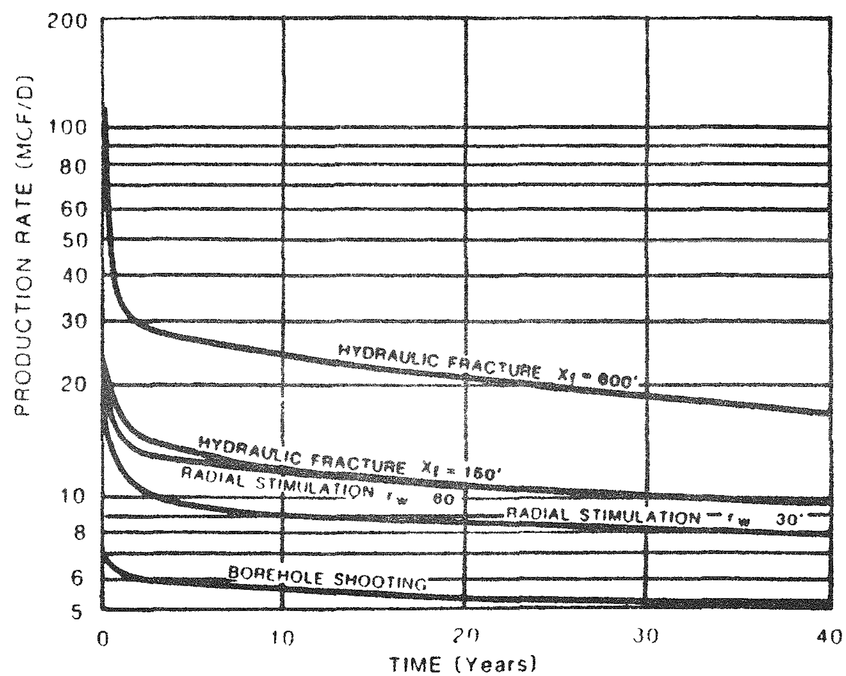
• DRILLABLE AREA (ACRES)	1,690,080
• RECOVERABLE GAS w/BOREHOLE SHOOTING (BCF)	636

STIMULATION TECHNOLOGY	CUMULATIVE RECOVERY (MMCF/WELL) 10 YRS	40 YRS
• BOREHOLE SHOOTING	21	79
• RADIAL STIMULATION		
-- rw 30'	36	128
-- rw-60'	47	164
• VERTICAL FRACTURE		
-- xf-150'	49	168
-- xf-600'	103	320

CUMULATIVE GAS RECOVERY



GAS PRODUCTION RATE

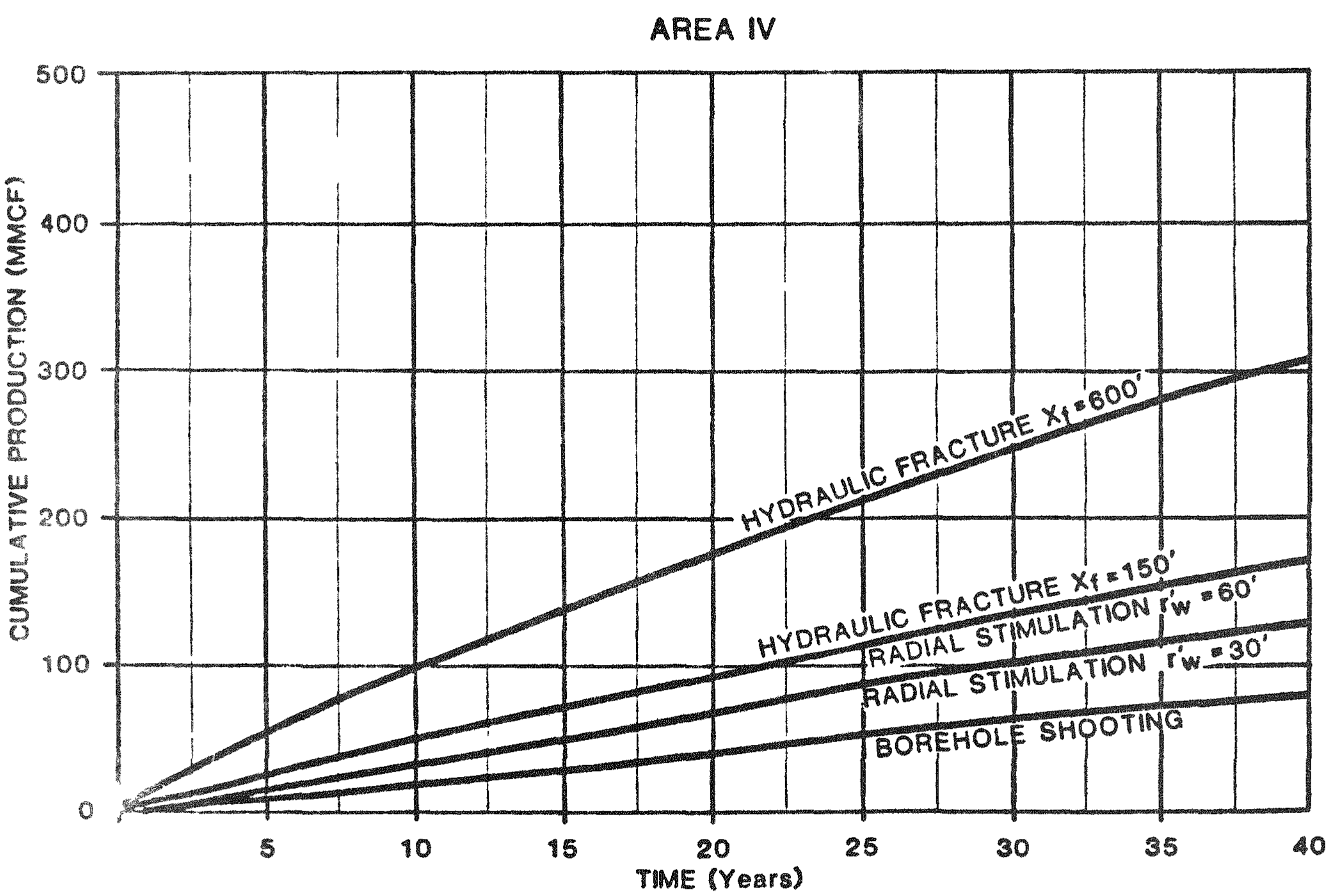


CUMULATIVE GAS RECOVERY BY TYPE OF STIMULATION (MMcf)

(One Well Per 160 Acres)

AREA IV

Year	Stimulation Method				
	Borehole Shooting	Small Radial Stimulation $r'_w = 30'$	Large Radial Stimulation $r'_w = 60'$	Small Vertical Fracture $x_f = 150'$	Large Vertical Fracture $x_f = 600'$
1	2.2	3.8	5.1	5.4	12.2
5	10.7	18.4	24.4	25.6	55.8
10	21.1	35.6	47.0	49.0	103.4
20	41.1	68.1	88.7	92.0	185.5
40	79.1	127.9	163.9	168.4	320.0

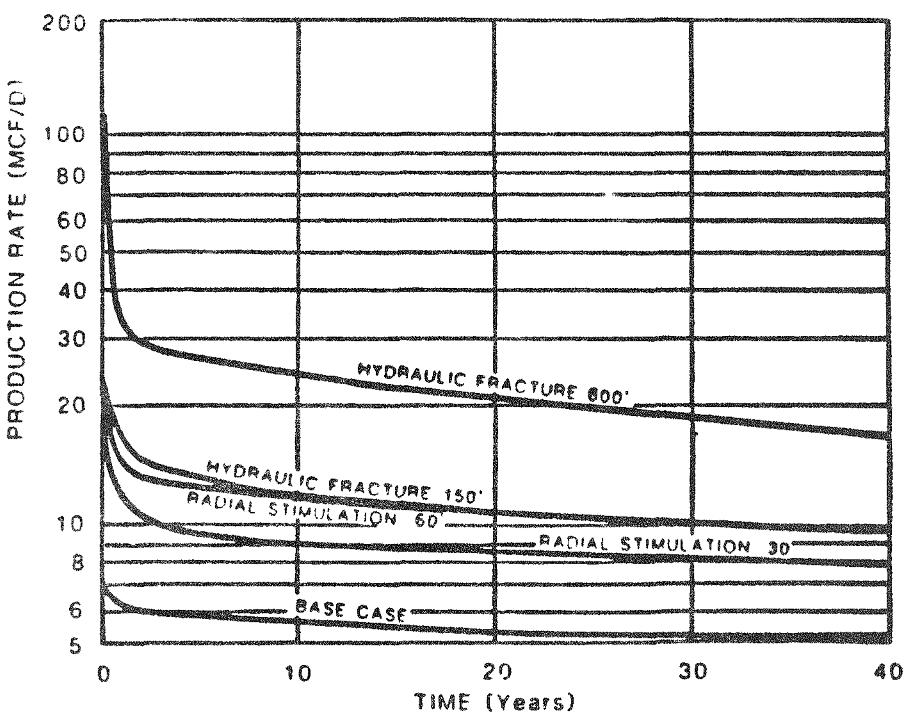


AVERAGE DAILY GAS PRODUCTION BY TYPE OF STIMULATION (Mcf/d)

AREA IV

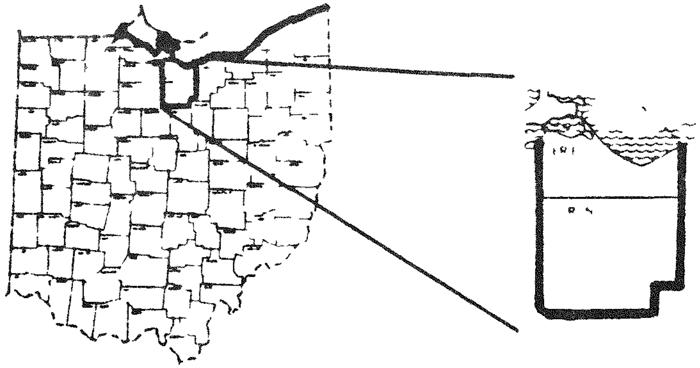
	Stimulation Method				
Year	Borehole Shooting	Small Radial Stimulation r'_w=30'	Large Radial Stimulation r'_w=60'	Small Vertical Fracture x_f=150'	Large Vertical Fracture x_f=600'
1	6	11	14	15	32
5	6	10	13	13	28
10	6	9	12	12	25
20	5	9	11	11	21
40	5	8	10	10	17

GAS PRODUCTION RATE



SUMMARY OF OHIO DEVONIAN SHALE GAS POTENTIAL

AREA V



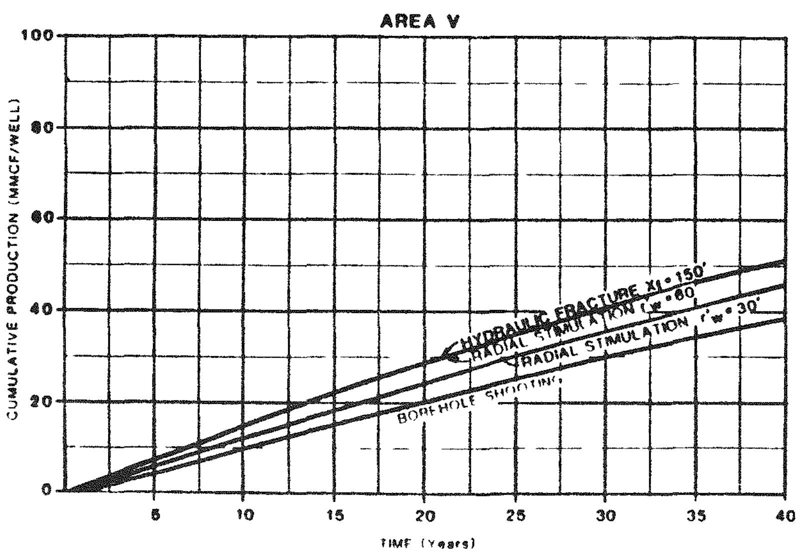
BASIC DATA

KEY RESERVOIR PROPERTIES	
• DEPTH (ft)	365
• ROCK PRESSURE (psig)	90
• GAS CONTENT (Mcf/AF)	200
• "NET" THICKNESS (ft)	10
• FRACTURE PERM (md)	4 429
• INIT OPEN FLOW (Mcf/D)	7
• PERM ANISOTROPY (ratio)	8 1
• FRACTURE INTERSECTION ANGLE (°)	40
• FRACTURE SPACING (ft)	20

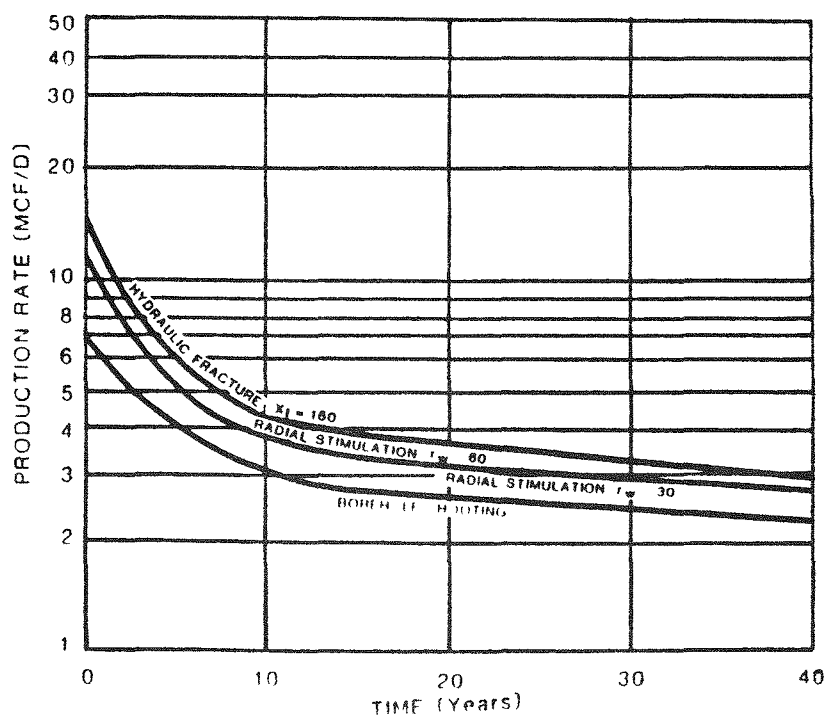
GAS POTENTIAL	
• DRILLABLE AREA (ACRES)	200,320
• RECOVERABLE GAS w/BOREHOLE SHOOTING (BCF)	49

STIMULATION TECHNOLOGY	CUMULATIVE RECOVERY (MMCF/WELL) 10 YRS	40 YRS
• BOREHOLE SHOOTING	11	39
• RADIAL STIMULATION		
-- rw-30'	14	47
-- rw-60'	15	51
• VERTICAL FRACTURE		
-- xf-150'	14	50

CUMULATIVE GAS RECOVERY



GAS PRODUCTION RATE

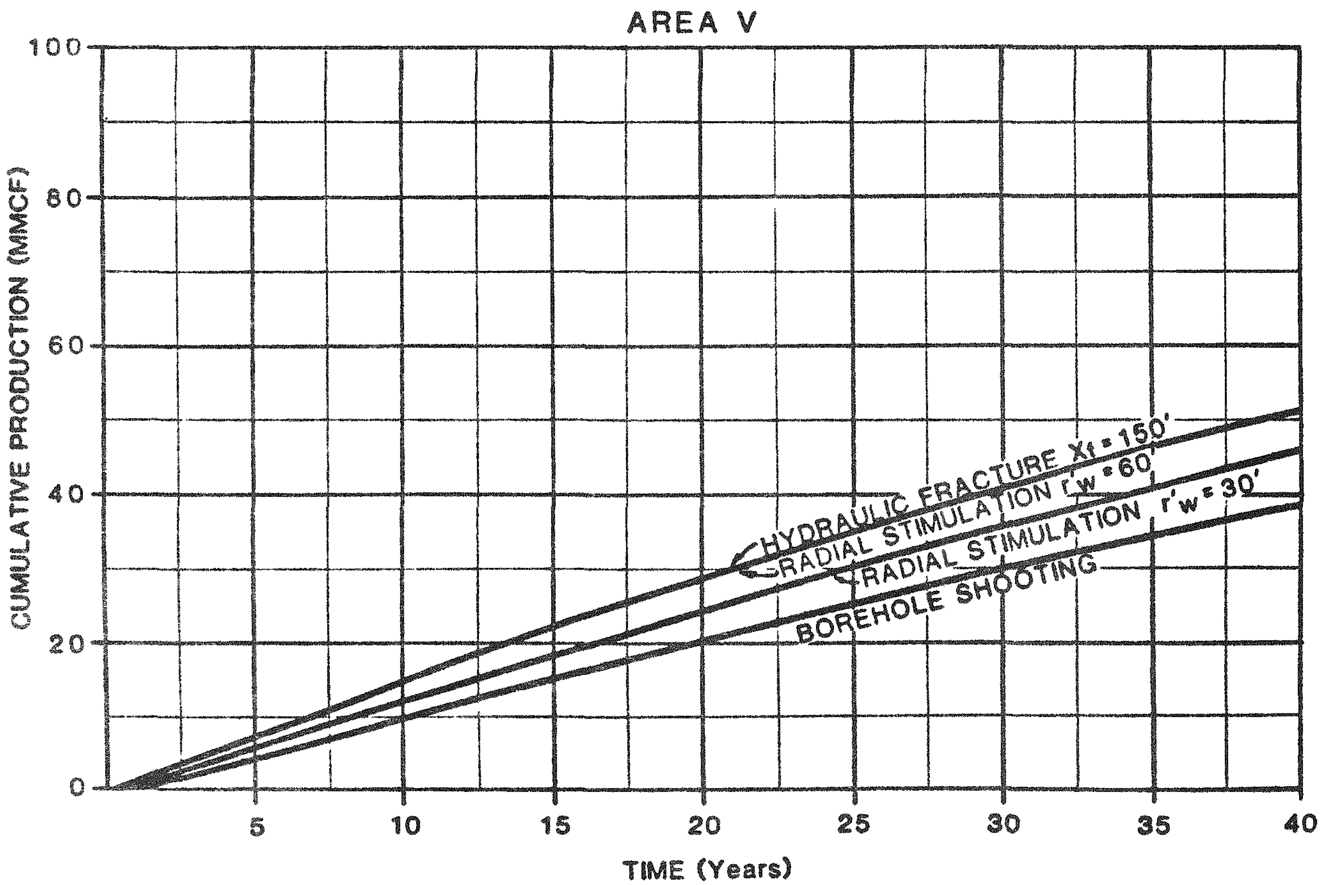


CUMULATIVE GAS RECOVERY BY TYPE OF STIMULATION (MMcf)

(One Well Per 160 Acres)

AREA V

Year	Stimulation Method			
	Borehole Shooting	Small Radial Stimulation $r'_w = 30'$	Large Radial Stimulation $r'_w = 60'$	Small Vertical Fracture $x_f = 150'$
1	1.2	1.5	1.7	1.6
5	5.6	7.0	7.7	7.5
10	10.8	13.6	14.8	14.5
20	20.8	25.8	28.0	27.5
40	38.8	47.2	51.0	51.0

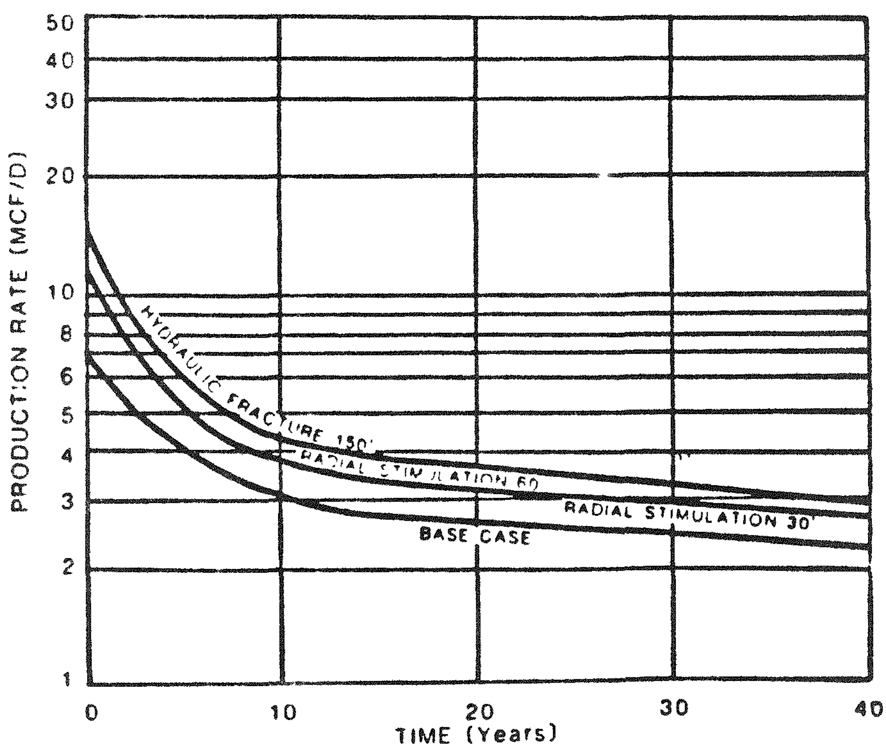


AVERAGE DAILY GAS PRODUCTION BY TYPE OF STIMULATION (Mcf/d)

AREA V

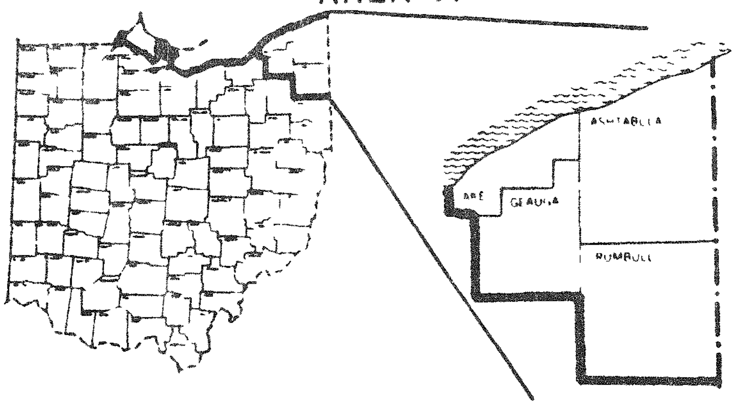
Year	Borehole Shooting	Small Radial Stimulation $r'_w = 30'$	Large Radial Stimulation $r'_w = 60'$	Small Vertical Fracture $x_f = 150'$
	Stimulation Method			
1	3	3.8	4.0	4.1
5	3	3.7	4.0	4.0
10	3	3.5	3.8	3.8
20	2.6	3.2	3.5	3.4
40	2.3	2.7	2.9	2.8

GAS PRODUCTION RATE



SUMMARY OF OHIO DEVONIAN SHALE GAS POTENTIAL

AREA VI



BASIC DATA

KEY RESERVOIR PROPERTIES

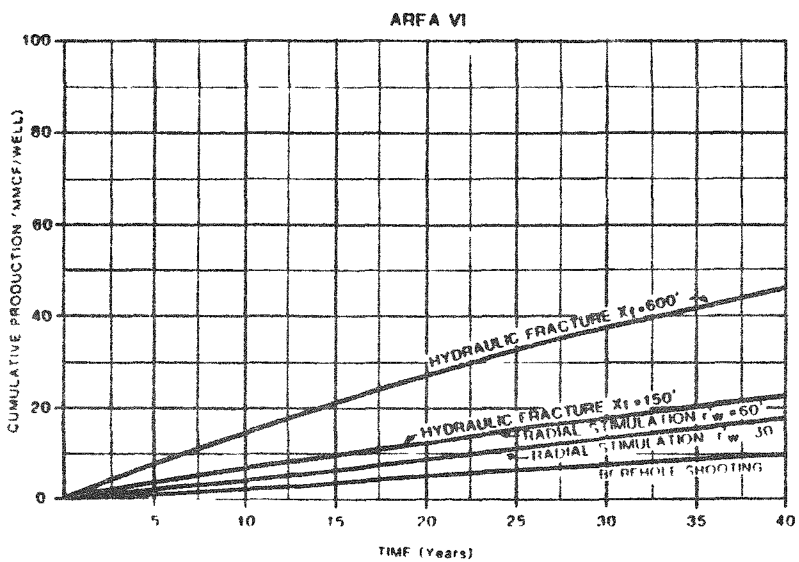
• DEPTH (ft)	2,135
• ROCK PRESSURE (psig)	135
• GAS CONTENT (Mcf/Af)	50
• "NET" THICKNESS (ft)	100
• FRACTURE PERM (md)	02
• INIT OPEN FLOW (Mcf/D)	1
• PERM ANISOTROPY (ratio)	8:1
• FRACTURE INTERSECTION ANGLE (°)	40
• FRACTURE SPACING (ft)	20

GAS POTENTIAL

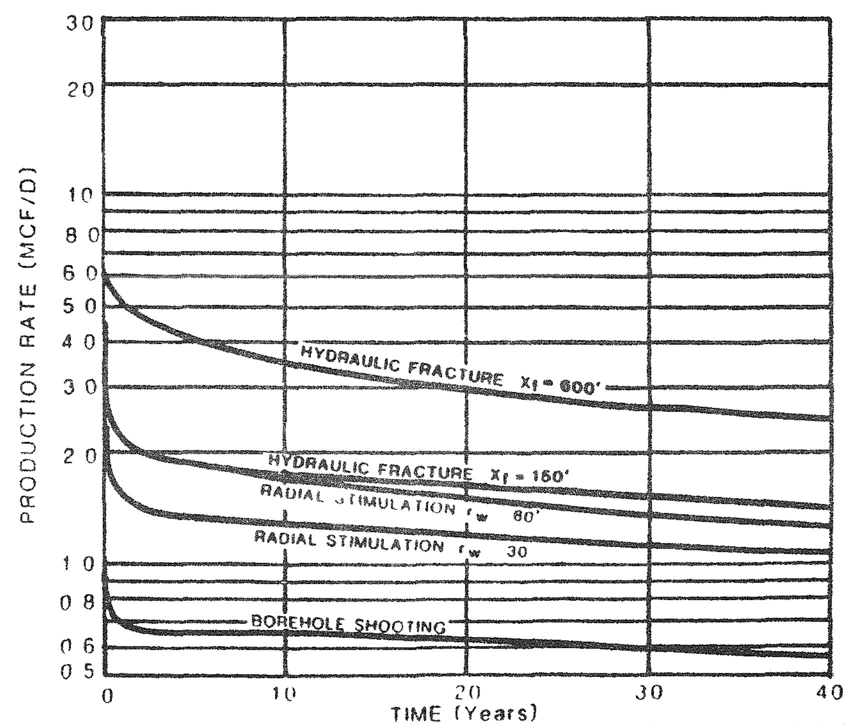
• DRILLABLE AREA (ACRES)	662,560
• RECOVERABLE GAS w/BOREHOLE SHOOTING (BCF)	41

STIMULATION TECHNOLOGY	CUMULATIVE RECOVERY (MMCF/WELL) 10 YRS	40 YRS
• BOREHOLE SHOOTING	3	10
• RADIAL STIMULATION		
-- rw-30'	5	18
-- rw-60'	7	24
• VERTICAL FRACTURE		
-- Xf-150'	7	22
-- Xf-600'	16	47

CUMULATIVE GAS RECOVERY



GAS PRODUCTION RATE

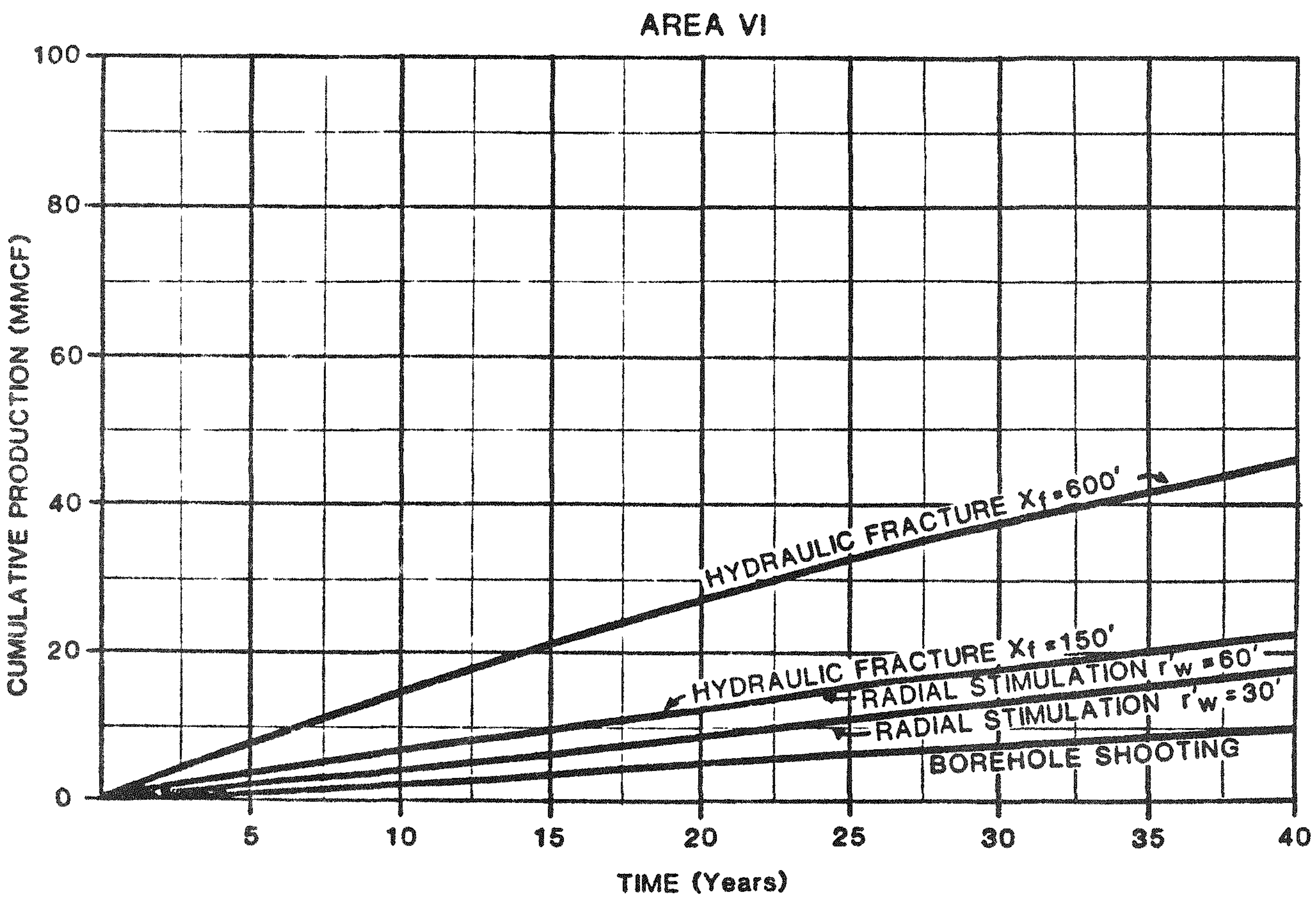


CUMULATIVE GAS RECOVERY BY TYPE OF STIMULATION (MMcf)

(One Well Per 160 Acres)

AREA VI

	Stimulation Method				
Year	Borehole Shooting	Small Radial Stimulation $r'_w = 30'$	Large Radial Stimulation $r'_w = 60'$	Small Vertical Fracture $x_f = 150'$	Large Vertical Fracture $x_f = 600'$
1	0.3	0.5	0.8	0.7	1.9
5	1.3	2.6	3.6	3.5	8.4
10	2.6	5.0	6.9	6.6	15.4
20	5.1	9.5	12.9	12.3	27.4
40	9.8	17.7	23.6	22.4	47.0

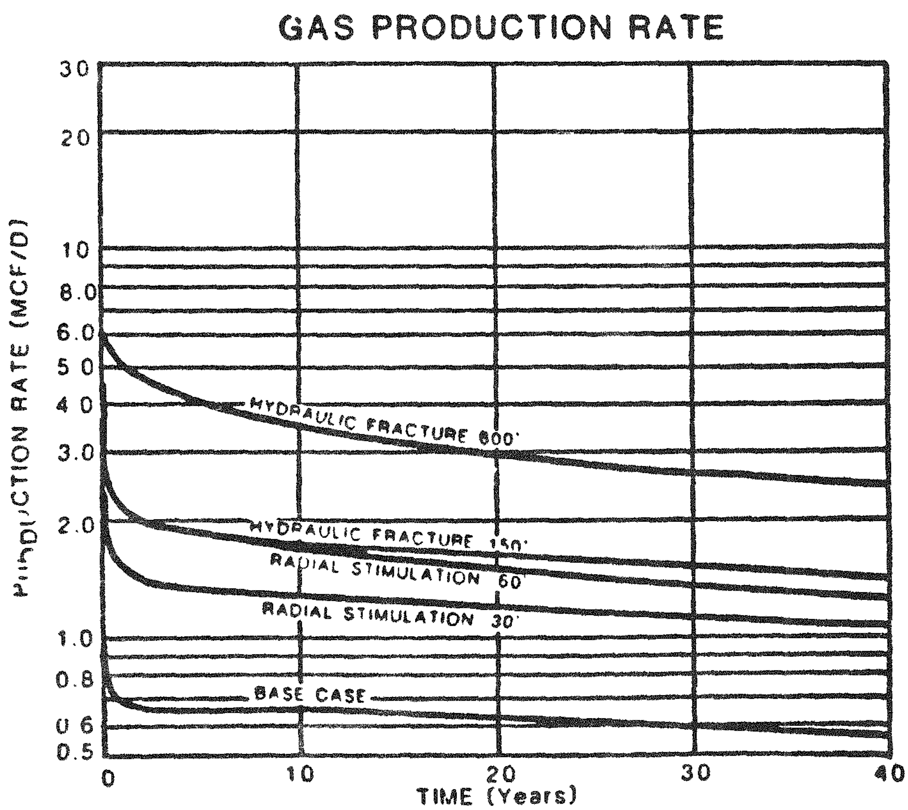


AVERAGE DAILY GAS PRODUCTION BY TYPE OF STIMULATION (Mcf/d)

AREA VI

Year	Borehole Shooting	Small Radial Stimulation r'_w=30'	Large Radial Stimulation r'_w=60'	Small Vertical Fracture x_f=150'	Large Vertical Fracture x_f=600'
1	0.7	1.5	2.0	2.0	4.9
5	0.7	1.4	1.9	1.8	4.2
10	0.7	1.3	1.7	1.7	3.7
20	0.7	1.2	1.6	1.5	3.0
40	0.6	1.1	1.4	1.3	2.5

Stimulation Method



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