MORGANTOWN
ENERGY
TECHNOLOGY
CENTER

DOE/METC-86/0231
(DE86001038)

Eastern Gas Shales

Technology Status Report

January 1986

U. S. DEPARTMENT OF ENERGY
OFFICE OF FOSSIL ENERGY
MORGANTOWN ENERGY TECHNOLOGY CENTER
MORGANTOWN, WEST VIRGINIA

DISCLAIMER

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

The report has been reproduced directly from the best available copy.

Available from the National Technical Information Service, U.S. Department of Commerce, Springfield, Virginia, 22161.

Price: Printed Copy AO2
Microfiche A01

Codes are used for pricing all publications. The code is determined by the number of pages in the publication. Information pertaining to the pricing codes can be found in the current issues of the following publications, which are generally available in most libraries: *Energy Research Abstract (ERA); Government Reports Announcements* and *Index* (GRA and I); *Scientific and Technical Abstract Reports* (STAR); and publication NTIS PR 360 available from NTIS at the above address.

DOE/METC-86/0231
(DE86001038)
Distribution Category UC-92a

MORGANTOWN ENERGY TECHNOLOGY CENTER
TECHNOLOGY STATUS REPORT

Eastern Gas Shales

Unconventional Gas Projects Branch
Extraction Projects Management Division

U.S. Department of Energy
Office of Fossil Energy
Morgantown Energy Technology Center
P.O. Box 880
Morgantown, West Virginia 26507-0880

January 1986

PREFACE

This report describes the state of the art in technology on the subject resource, a part of DOE's research program on unconventional gas recovery. It discusses the technical issues warranting investigation and focuses on current activities that are being supported by DOE. As presented, it is intended to provide an in-depth perspective of the knowledge base required to develop concepts for recovery. As new information becomes available, it will be summarized annually. This will permit timely transfer to the private sector, and then, when market conditions are more favorable, unconventional gas resources can be readily developed.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

The goal of eastern gas shales research is to develop the scientific and engineering knowledge base on the recovery of natural gas from shale formations that underlie the Appalachian, Illinois, and Michigan Basins. This research is an integral part of the Unconventional Gas Recovery (UGR) activity, which is a multidisciplinary effort sponsored by the U.S. Department of Energy (DOE) to quantify where future gas reserves can be found.

Eastern gas shales research has been successful in characterizing the geology, geochemistry, and resource magnitude of the Appalachian Basin, and in defining the gas-producing mechanism and drainage pattern in an established area of production near the middle of the basin. In addition, an offset well test (two wells offset to a producing well) established reservoir flow behavior and resulted in the identification of the potential for infill drilling of existing shale gas fields. Infill drilling has been predicted to be a cost-effective strategy for exploitation of gas resources within known producing areas. In areas of established production (eastern Kentucky, southern and western West Virginia, and southern Ohio), the 3 trillion cubic feet (Tcf) produced to date could be increased thirtyfold without further exploration.

Currently, research focuses on fundamental reservoir properties from wells of opportunity, and on the installation of a second offset well test site for understanding reservoir flow behavior. This research entails gathering reservoir property data from 10 sites that have favorable geology and geochemistry in areas of non-established production. This information will quantify the magnitude of matrix and fracture porosity and permeability and reservoir anisotropy, and will improve the ability to quantify technically recoverable resources for these areas of unknown potential.

Also under study are methods to increase recovery efficiency from a directionally drilled well in an area of historical production, wherein less than 10 percent of the available gas-in-place is typically produced by stimulated vertical wells. Analysis of shale gas production mechanisms indicates that an increase in the amount of surface area connected to the borehole may result in more of the adsorbed gas being released and produced over the entire life of the well. Increased recovery efficiency is thought to be achievable using a directionally deviated well that can be designed to cross natural fractures and can be stimulated to increase the surface area in contact with the borehole. The existing reservoir model (SUGAR-MD) has been modified to permit the expected performance of stimulated, deviated wells to be simulated. The drilling, coring, logging, and testing of a directionally deviated well is a major field verification effort that measures the key reservoir properties (natural fracture spacing, in situ stress, productive interval, formation permeability, and porosity) used in the simulator and also the productivity improvement over that of stimulated vertical wells in the area (available baseline data). Results could provide important guidelines to industry that may augment gas recovery efficiency, from 3 Tcf of the available 160 Tcf in place to some multiple of that, using infill drilling and more efficient production practices.

1.0 INTRODUCTION

Natural gas from the Devonian member of the eastern gas shales has had a long production history. The first Devonian shale gas well was drilled in 1821 near Fredonia, New York. Production subsequently occurred in Ohio and West Virginia around 1860. Modest field development began in the Big Sandy Field of Eastern Kentucky in 1914 and has continued up to the present time. Cumulative production from the shales during all the years of production has been less than 3 Tcf. Annual production is only about 0.1 Tcf per year.

Typically, shale gas wells have low volume and low pressure. Their low rate of decline accounts for some wells having a 50-year life. Production from shale gas wells is at first relatively high (exceeding 200 MCFD [thousand cubic feet per day]), but declines steadily to a base level that can remain constant for 10 to 30 years. In the early part of the well's life (the first 5 years), the high production rate is attributed primarily to the free gas contained in the fracture network immediately connected to the wellbore, and to pore gas that readily migrates to the wellbore. Later, production comes from gas that diffuses through and desorbs from the shale matrix. This usually is sustained over a long period of time (decades). The relative contribution of the three distinct sources of gas in the shale is not completely understood.

There are alternative interpretations for why shale gas wells have a sustained base level and a long life. One interpretation is that this base level is primarily absorbed gas that is being released as the pressure drops. Another explanation is that the base level gas is primarily gas from other intervals that are connected to the primary interval by the vertical fracture network in the shale. Deciphering the relative roles of the two mechanisms is critical to estimating the recoverable resource. At one extreme, if absorbed gas predominates and shale strata are independent reservoirs, then new target intervals could be identified that may be a source of gas in the future, and the recoverable gas estimate may be high. At the other extreme, if there is little absorbed gas to produce, and vertical communication between organically rich shale intervals is evident, then the number of targets for future development is drastically reduced and the recoverable resource estimate will be low.

Because of these producing characteristics, shale gas has been used primarily for regional domestic markets or by small industries, and has never been considered as part of the national reserve. However, with research on advanced exploration and extraction technologies, a greater portion of the shale gas resource may be recoverable. This may be sufficient to meet the 2 Tcf per year demand of the regional eastern market.

2.0 TECHNOLOGY DESCRIPTION

2.1 RESOURCE BASE

The eastern gas shales are middle Devonian through Mississippian in age. These formations underlie much of the Appalachian, Michigan, and Illinois basins. Production has been mainly from the Appalachian Basin, with much smaller quantities of gas produced from the Michigan and Illinois basins.

Recent attention has been focused on shales of Devonian age in the western portion of the Appalachian Basin. Of the approximately 160,000 square miles in the western Appalachian Basin, about 40 percent is underlain by Devonian black and brown shale deposits at depths of less than 4,000 and 8,000 feet, and the remainder at depths greater than 8,000 feet.

As eastern gas shales research has evolved, the geologic data base has been expanded and the large areas of Devonian shale have been subdivided into smaller geologic provinces, as shown in Figure 1. Each province reflects certain geologic problems and associated technology development needs. The provinces are described as follows:

- Province 1 — Highly Productive Appalachian Producing Areas. Province 1 contains the Big Sandy Field and other, smaller, fields where most of the production from Devonian shales has occurred. Ongoing refinements of current development practices to increase recovery efficiency are taking place at fields within this province.
- Province 2 — Ohio and Related Areas. Province 2 includes eastern Ohio, northwestern Pennsylvania, northwestern New York, and parts of northwestern West Virginia. Shales in Province 2 have been marginally productive in certain areas and are potential targets for dual completion (a second producing interval) in conjunction with deeper conventional targets. Technology development efforts are directed toward dual completion techniques.
- Province 3 — Appalachian Front. Shales in Province 3 are located along the Appalachian

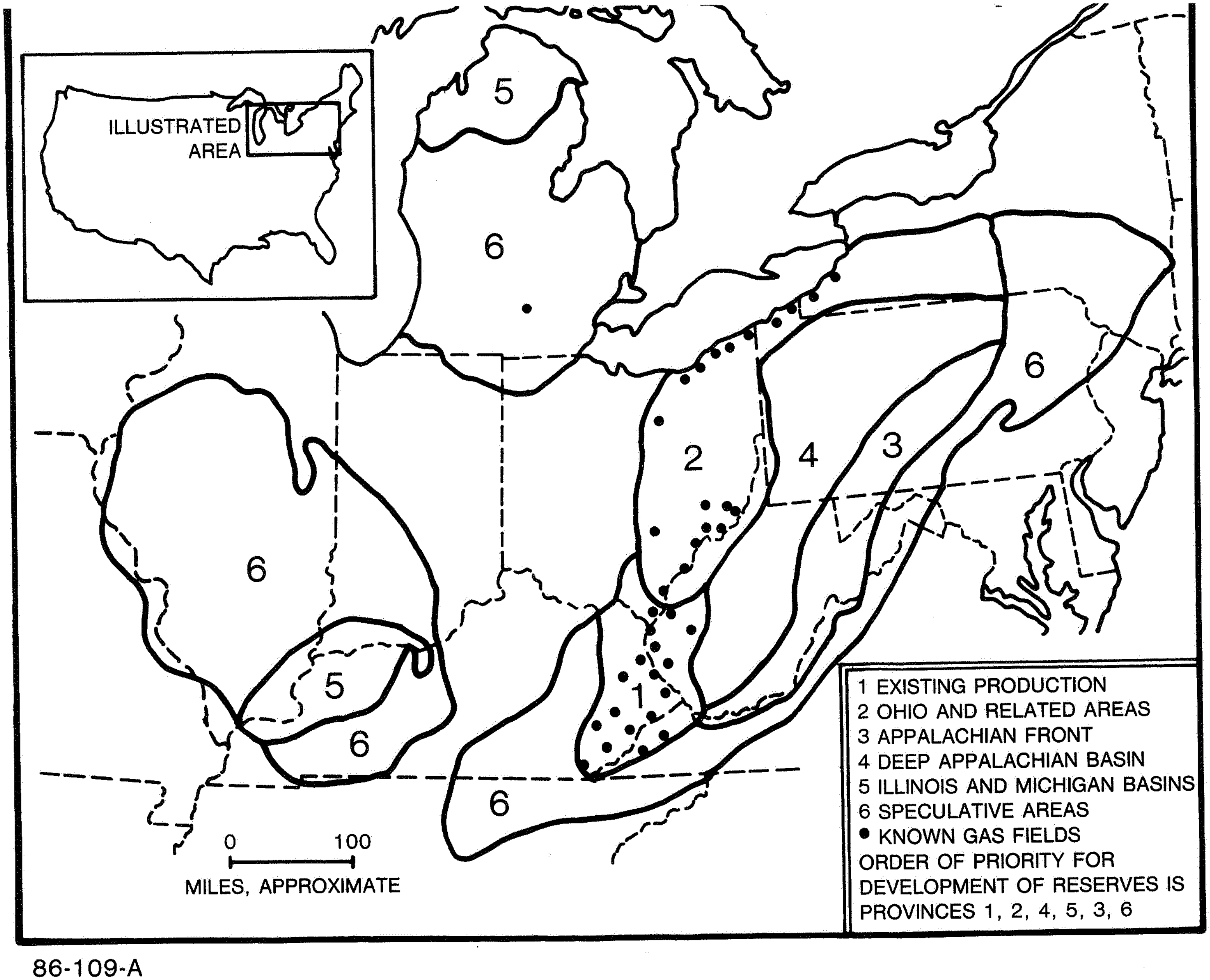


FIGURE 1. LOCATIONS OF EASTERN GAS SHALE PROVINCES

Front, which is characterized by complex geologic structures and deeper target formations. This province requires a large resource characterization effort to locate high concentrations of gas in deep complex structures. If significant amounts of gas are located, extraction technologies will need considerable improvement to ensure economical recovery.

- Province 4 — Deep Appalachian Basin. Shales in Province 4 occur within the central northeastern portions of the Appalachian Basin at depths generally exceeding 5,000 feet. As in Province 3, the depth of these targets has precluded detailed characterization and delineation of productive shale gas areas because of costs.
- Province 5 — Illinois and Michigan Basins. Potentially productive shales exist in Province 5. Locating areas where geologic conditions are similar to those in the productive areas of Province 1 is the primary objective.
- Province 6 — Speculative Resource Areas. Province 6 consists of areas that are presently considered nonproductive. Also in this category are areas where gas shows may have been reported, but for which little or no data exist. Speculative resource areas include both deep and shallow occurrences in parts of New York, Pennsylvania, Virginia, Tennessee, Illinois, Indiana, Oklahoma, and Texas.

2.2 RESOURCE ASSESSMENT

The Devonian shales have great potential for becoming a major contributor to the U.S. gas supply. Devonian shale gas resources of the Appalachian, Michigan, and Illinois Basins are shown in Table 1. The National Petroleum Council estimates that from 17 to 50 Tcf could be recoverable.

TABLE 1. DEVONIAN SHALE GAS RESOURCE ESTIMATES FOR THE APPALACHIAN, MICHIGAN, AND ILLINOIS BASINS

Basin	Resource (Tcf)	Area (mi^2)
Appalachian	225 to 1,861	111,100[1]
Michigan	74[1]	35,400[1]
Illinois	86[1]	28,150[1]

[1] National Petroleum Council (1980)

Although the Devonian shales are a large natural gas resource, they remain unattractive to private industry. Therefore, two main objectives of DOE eastern gas shales research are the following:

- Development of production methods for unproven areas having favorable geology and geochemistry.
- Quantification of reservoir parameters and production performance to permit systematic assessment of reserves.

Cooperative efforts with industry are intended to accelerate accomplishment of the first objective. Achievement of the second objective will help make policy decisions concerning the role of Devonian shales in the nation's future energy supply, and will provide a basis for commercial development opportunities in gas supply.

3.0 STATE OF TECHNOLOGY

The eastern gas shales exhibit low shale matrix and fracture porosities, permeabilities, and rock pressures. Production is characteristically at the low rate of 10 to 50 MCFD and lasts as long as 30 to 40 years. Production generally occurs in geologic areas where natural fractures are abundant. These natural fractures act as flow channels for the gas. To obtain good production, it is usually necessary to connect as many natural fractures as possible to the wellbore by stimulating (fracturing) the shale.

Porosity is the void space in the reservoir rock in which hydrocarbons are stored. In conventional reservoirs, porosities generally range between 7 and 30 percent. In shales, matrix porosities are usually less than 1 percent. The shale fracture porosities, when considered with respect to the shale matrix, are usually less than 0.01 percent. Therefore, it is generally believed that the major portion of the gas is adsorbed in the shale matrix. As the gas contained in the fractures is produced into the wellbore, the shale matrix gas desorbs to replace it. However, the permeability of the matrix is so low that the gas is removed from the fractures faster than the gas can flow from the matrix into the fractures; hence, production declines.

The objective of stimulating Devonian shale is to initiate and propagate fractures that will intersect pre-existing natural fractures. This will increase the permeability of the reservoir, and provide a network by which natural gas can flow to the borehole.

In regions where multiple sets of natural fractures occur, a multidirectional fracturing process is desired. Some multidirectional stimulation techniques nclude (1) borehole shooting with 80-percent gelled ıitroglycerine, (2) borehole shooting with an en- ;rgy pulse tailored to the formation, (3) detonation ɔf displaced chemical explosives, and (4) the den- lritic fracturing process. In regions where natural 'ractures are sparse and the distance between frac- ures is great, a fracturing technique that produces ı long induced fracture is desired. Two fracturing echniques that accomplish this are (1) conventional ıydraulic fracturing and (2) massive hydraulic 'racturing.

:n all instances, many factors need to be controlled ınd studied further, including improvement of ;timulation designs, diagnosis of orientation, and :ontainment of the fracture. Model validation tests ıre planned in the Devonian shale so that tests and :xperiments can be conducted in situ and directly ɔbserved. Other important areas of study include 'racture spacing, flow characteristics, tests for an- sotropy and interference between wells, and reser- ,oir potential. Further knowledge in these areas vill help in the design of well spacing, and in simu- ations of production and stimulations. .

?revious efforts have been successful in characteriz- ng shale gas geology, geochemistry, and resource nagnitude within the Appalachian Basin, and in lefining the gas-producing mechanism and drain- ıge pattern in an established area of production. \n upsurge in the drilling, testing, and stimulation ɔf gas shales by industry in the Appalachian Basin ıas been encouraged by DOE-sponsored research. ₹ecently, a number of major studies and activities ıave been completed that provide a basis for ad- ,ancing the understanding of the Devonian gas :hales. One of these is an offset well test (two wells ɔffset to a producing well) that established reservoir low behavior and resulted in the identification of he potential for infill drilling of existing gas fields. :nfill drilling has been predicted to be a cost- :ffective strategy for the recovery of shale gas from :stablished regions of production. Recent accom- ɔlishments include the following:

- Installation of STEALTH/CAVS, a computer code that simulates dynamic wellbore stimulations.
- Completion of the topical report entitled "A Perspective on Modeling Tailored-Pulse Loading (TPL) for Borehole Stimulation" (Swift 1984).
- Completion of the Clinton Sand Data Analysis to permit an assessment of dual completion potential in Ohio.
- Completion of a small study to determine the geologic and engineering factors that explain the production performance from eastern tight formations.

The first two accomplishments will help to understand fracturing-of-reservoir-flow behavior and what can be done to improve production performance. The last two accomplishments will help to improve production in selected areas where both sands and shales exist.

4.0 CURRENT ACTIVITIES

DOE has conducted eastern gas shales R&D projects in four major areas: geologic research; reservoir assessment, diagnostics, and fracturing research; production research; and technical integration and evaluation. Activities within these areas are described in the following sections.

4.1 GEOLOGIC RESEARCH

Geologic research is required to characterize eastern gas shale provinces, and to develop successful exploration rationales. Stratigraphic, structural, sedimentological, physical, and chemical data have been collected to identify gas-bearing fracture systems. Field work has included coring and logging to provide samples and data for laboratory work. Laboratory research has included chemical , physical, elemental, and mineralogical studies to determine the stratigraphic sources of gas and the degree of fracturing within the reservoirs. Resource characterization has been performed through contracts with universities, state geological surveys, research institutes, and private industry. Methods of locating gas-bearing, naturally fractured reservoirs have been developed and improved.

A major study, discussed in more detail in Section 4.3, will provide more geological information in areas of unknown potential and different stratigraphic horizons. Logging, coring, permeability, porosity, and geochemical data will be collected.

Current geologic research includes a geologic assessment of the Ordovician shale. This study, performed by the U.S. Geological Survey (USGS) under contract to DOE's Morgantown Energy Technology Center (METC), has shown that gas may have accumulated in the Ordovician black shale of the Appalachian Basin. Organic carbon analyses and pyrolysis assays (the thermal breakdown of a formation sample into simple components) have been completed for 35 samples from the east Tennessee outcrop area. Preliminary interpretation of the sample analyses suggests that the shales contain sufficient amounts of organic carbon to generate hydrocarbons upon maturation. The general level of maturation suggests that dry gas could have accumulated in stratigraphic or structural reservoir traps. Further research will confirm whether methane gas exists in Ordovician black shale deposits.

4.2 RESERVOIR ASSESSMENT, DIAGNOSTICS, AND FRACTURING RESEARCH

New diagnostic tools and stimulation approaches are being developed. In addition, the ability to forecast shale reservoir performance is being developed for various extraction methods when they are applied to particular geologic provinces. These activities require basic and applied R&D in the laboratory and in the field, as well as the development and use of models. Models describe the present understanding of stimulation, gas flow, and economic parameters related to shale fracturing and gas production.

The development of SUGAR-MD, a general purpose reservoir simulating model that addresses dual porosity, anisotropy, the natural fracture system, and induced fractures, provides the capability to forecast shale reservoir performance. Modeling with SUGAR-MD has included both history matching to determine reservoir parameters, and infill drilling studies to predict increases in gas recovery. Achievements in basic research have been the installation of the STEALTH/CAVS model and the completion of porosity and permeability measurements on Devonian shale core samples.

Numerical models can aid in understanding general phenomena of explosive wellbore stimulation. Models have been developed that precisely account for the chemical energy release of explosive detonation (or propellant deflagration), the expansion of the wellbore fluids, the stress wave propagation and failure in the confining rock, and the interactive responses between fluid flow, fracture growth, and fracture void modifications.

The STEALTH/CAVS model provides a computational description of the essential physical phenomena of dynamic wellbore stimulation. These phenomena include:

- Wellbore pressure loading in an explicit time sequence.
- Stress wave propagation through the reservoir rock.
- Fracture initiation and growth resulting from tensile stress waves.
- Fracture opening and wellbore fluid penetration.
- Internal fluid pressurization assisting crack opening and extension.
- Fracture propping during stress wave subsidence, fluid pressure equilibrium, and crack reclosure.

The shear fracture sublogic of CAVS (Crack And Void Strain) was developed during an explosive rock fragmentation study. The shear model has been computationally coupled to the tensile fracture model and to standard STEALTH elastic and plastic models. This expansion of the CAVS model has recently been installed on METC's computer.

The CAVS model has been constructed to represent tensile fracture of brittle materials in one-, two-, and three-dimensional geometries and has been applied in the analysis of quasi-static and stress wave propagation problems. The CAVS model provides the appropriate coupling between (1) the state of stress and strain associated with fracturing, and (2) explicit descriptions of crack initiation, propagation, opening, and reclosing. The discrete fractures represented by the model are particularly important in comparative analyses of fracture development and permeability enhancement for wellbore stimulation treatments. Figure 2 shows the model components used for the various calculations of a fracture and fragmentation analysis.

Although STEALTH/CAVS is the most complete dynamic wellbore stimulation model, research suggests it should be made more complete and general, and, therefore, more applicable to a wider variety of problems.

Laboratory measurements of permeability and porosity have been completed for Devonian shale core samples from four areas within the producing region of the basin. Table 2 shows the permeability and porosity values for these cores under two confining pressures.

These measurements confirm measurements of past studies and the belief that the Devonian shale is a very tight reservoir rock. Permeability measurements show that the shale is about six to nine orders of magnitude less permeable than conventional reservoir rocks. Porosity values verify that most of the gas is desorbed in the shale matrix. These permeability and porosity values will be used to provide better estimates of porosity and permeability

Model Components

- Explosive and rock initial conditions (STEALTH Input)
- Explosive initiation (STEALTH Timing)
- Explosive detonation and expansion (Material EOS Model)
- Compressive stress waves in rock (STEALTH, Material Model)
- Tensile stress waves in rock (STEALTH, Material Model)
- Rock failure from stress waves
  - Plasticity (Material Model)
  - Tensile fracture (CAVS)
  - Shear fracture (CAVS)
- Explosive gas generation (Material Model)
- Gas penetration and pressurization of fractures (CAVS)
- Fracture extension and opening
  - Sustained stress waves (STEALTH, Material Model)
  - Internal gas pressure within fractures (CAVS)

EG&G A-85-073-01

FIGURE 2. FRACTURE AND FRAGMENTATION ANALYSIS

TABLE 2. POROSITY AND PERMEABILITY OF DEVONIAN SHALE CORE SAMPLES

Core Sample	Porosity		Permeability	
	P_c* = 1,750	P_c = 3,000	P_c = 1,750	P_c = 3,000
Gallia Co., OH	.78%	.80%	~ 1 nd**	***
Meigs Co., OH	.15%	.10%	~ 1 nd	< .2 nd
Mason Co., WV	.10%	.22%	66 nd	14 nd
Leslie Co., KY	.12%	.26%	22 nd	5 nd

* Confining pressure on core.
** nd = 10^{-9} darcy.
*** Insufficient data to make an estimate.

in reservoir models. Thus, the predictive capabilities of these models will be improved.

Existing hydraulic fracturing models are considered to be inadequate for two reasons: (1) they do not consider interactions between induced and natural fractures, and (2) they are not versatile, that is, a model that was developed for the shale is not satisfactory for use with other projects.

Ohio State University (OSU) is developing a generalized hydraulic fracturing model. This model will consider interactions between induced and natural fractures; it will be useable in all project areas and will interface with SUGAR-MD. Therefore, once a reservoir is simulated with the hydraulic fracturing model, the reservoir will be ready for use in SUGAR-MD.

Current work by Science Applications, Inc. (SAI) will enhance the modeling effort by OSU. SAI is doing laboratory testing of the interactions between hydraulically and dynamically induced fractures and pre-existing fractures. SAI has developed a dimensionless fracture interaction equation that allows for the scaling of the physical world to laboratory work and for the selection of a material that is representative of the Devonian shale.

SAI has also completed testing of 14 hydraulically-induced and/or natural fracture interactions. Initial results show that for low angles of intersection ($\leq$ 30°), the induced fracture terminates, while for larger angles of intersection, the induced fracture crosses natural fractures. This information will provide industry with a guide for stimulation operations, and it will also be valuable input to fracture models.

Lawrence Livermore National Laboratory (LLNL) is developing new diagnostic tools and stimulation approaches. The two diagnostic tools involve the use of shear waves for determining natural fractures and in situ stress. LLNL is also studying TPL, a reservoir stimulation technique in which a controlled dynamic release of fluid energy pressurizes a wellbore to initiate multiple fractures. LLNL has recently published a topical report entitled "A Perspective on Modeling Tailored-Pulse Loading (TPL) for Borehole Stimulation" (Swift 1984).

TPL appears to be well suited for stimulating many of the naturally fractured gas-bearing deposits, such as Devonian shale, because it provides an effective way to connect the wellbore with preexisting fractures as illustrated in Figure 3. Success of the TPL technique depends not only on an understanding of the mechanisms and processes involved, but also on an awareness of its limitations.

Comprehensive modeling of TPL multiple fracturing requires attention to several interactive processes, including nonlinear mechanical deformation, fracturing, porous flow into fractures, and fluid flow in fractures. In addition, intrinsic conditions such as in situ stresses, natural fractures, and saturation must be accounted for, as well as the cumulative influence of all processes and conditions on the TPL fluid pressurization source.

Among the issues discussed in the LLNL topical report are the concepts of multiple fracturing based on observations, and intuitive interpretation of experimental data that aid in understanding the roles of fracture initiation and fracture extension. The report also assesses the value and limitations of past and current TPL stimulation models, along with requirements and suggestions for alternative approaches. Also discussed are ways to develop a unified hybrid model for TPL stimulation that comprehensively addresses several factors: preinitiation pressurization, initiation of multiple fractures, extension of multiple fractures, interaction of induced fractures with existing joints and fractures, and fluid flow within fractures.

West Virginia University (WVU) is currently developing analytical techniques for enhancing predictive capability in gas field development. This research involves parametric studies of gas field development and subsequent design of a well placement strategy. Also, WVU will develop automatic history matching (AHM) capability for current Devonian shale reservoir models. Analysis of field data is underway in preparation for the eventual development of the AHM procedure.

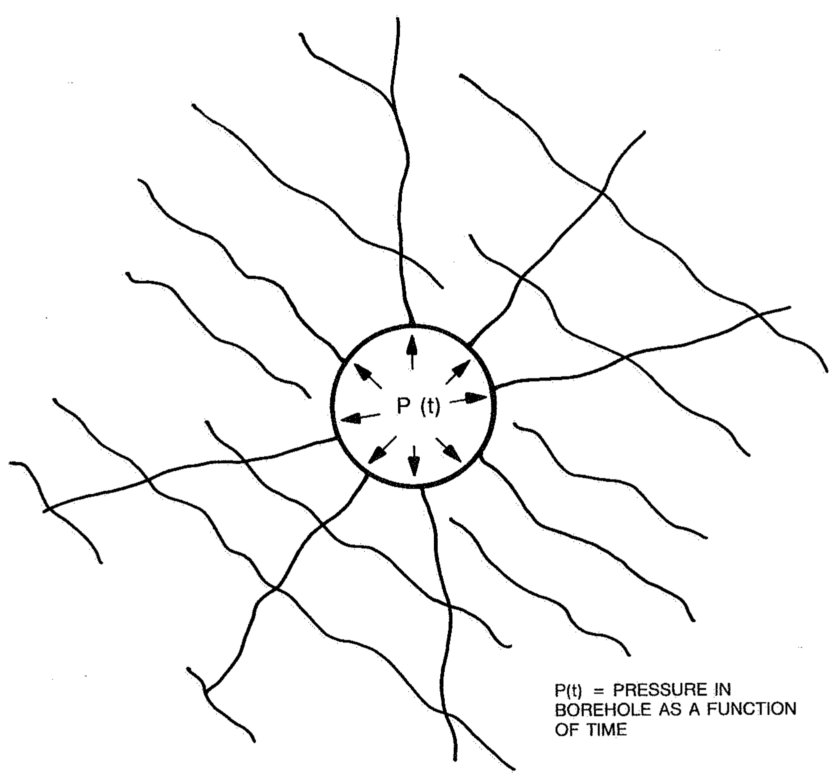


FIGURE 3. TPL STIMULATION OF A NATURALLY FRACTURED ZONE A-85-073-02

In general, AHM employs a combination of operations research tools and algorithms. An AHM procedure must contain three basic algorithms, which may well be intertwined rather than distinct. The three parts are: (1) a method for comparing model results with relevant historical data and testing deviations against stopping criteria; (2) a well-defined automatic procedure for refining parameter estimates between successive model runs; and (3) a computational code that efficiently coordinates model, reparameterization, and convergence checking.

Lack of convergence is a common problem in iterative calculations that often stems from purely computational limitations, but one can expect some history matching attempts to be inherently inexact. However, efforts will be made to solve this problem so that the algorithm will be capable of detecting nonconvergence computationally and soon enough to avoid costly, wasteful use of the computer.

4.3 PRODUCTION RESEARCH

Production research is directed at (1) developing effective stimulation methods for various geologic environments and testing these methods in field applications, (2) understanding reservoir flow behavior, (3) acquiring reservoir properties, and (4) determining recovery efficiencies of novel methods of shale production.

A major study is planned that will involve the testing of 10 wells and an offset well test facility in unproven areas (Figure 4). This study will provide information on areas and stratigraphic horizons that have a favorable potential for gas production, but that have not yet been the target of industry. It is hoped that these tests will result in a better understanding of reservoir flow behavior, which will lead industry to develop these areas of favorable production.

4.4 TECHNICAL INTEGRATION AND EVALUATION

Some of the recent accomplishments that have resulted from technical integration and evaluation efforts include (1) the environmental, health, and safety review for UGR activities, (2) the estimation of recoverable resources from the Devonian shales in Kentucky, (3) the evaluation of geologic and engineering factors that explain the production performance for eastern tight formations, and (4) the completion of a study on the Clinton sands of Ohio to determine factors affecting production.

4.4.1 Environmental Concerns

An environmental, health, and safety review was conducted to determine concerns associated with UGR technology and to recommend activities that might better define or ameliorate those concerns.

In comparison to many energy technologies, the potential environmental effects and concerns associated with UGR are relatively well known, as they are similar to those associated with conventional gas recovery. These effects include (1) land disturbance, erosion, and surface water contamination during initial drilling activities (and in some localities, during the construction of new collection and transmission pipelines); (2) water consumption in some arid or semiarid areas; and (3) water contamination from disposal of produced waters and brines, especially by underground injection. The potential for major effects appears to be relatively small. However, site preparation, drilling stimulation, gas production, and gas transmission may cause short-term problems in certain areas.

4.4.2 Estimates of Technically Recoverable Resources

The estimate of the technically recoverable gas from the Devonian shale in Kentucky was based on several data sources: (1) historical production data from 311 wells in 16 counties, (2) a compilation of geologic and reservoir data for the gas in place, (3) analysis and modeling of the dominant gas production mechanisms, and (4) examination of alternative stimulation and production strategies for most efficiently recovering the gas. Kentucky was divided into three geologic settings for this study, as shown in Figure 5.

- *Geologic Setting I* covers the eastern and southeastern part of the state and is characterized by the thick, radioactive, and organically rich Huron and Cleveland shales of Upper Devonian age. Below these contributing intervals is the deeper Rhinestreet shale, also highly radioactive. This setting includes a major portion of the Big Sandy Field with a nearly continuous area of production covering 3,000 square miles in most of Knott, Floyd, Martin, and Pike counties. Parts of the Big Sandy Field are also in Leslie, Letcher, Perry, Johnson, and Lawrence counties.
- *Geologic Setting II* is the second area that covers the east central portion of the state, where the Rhinestreet shale rapidly thins along the eastern boundary of the setting. The Huron

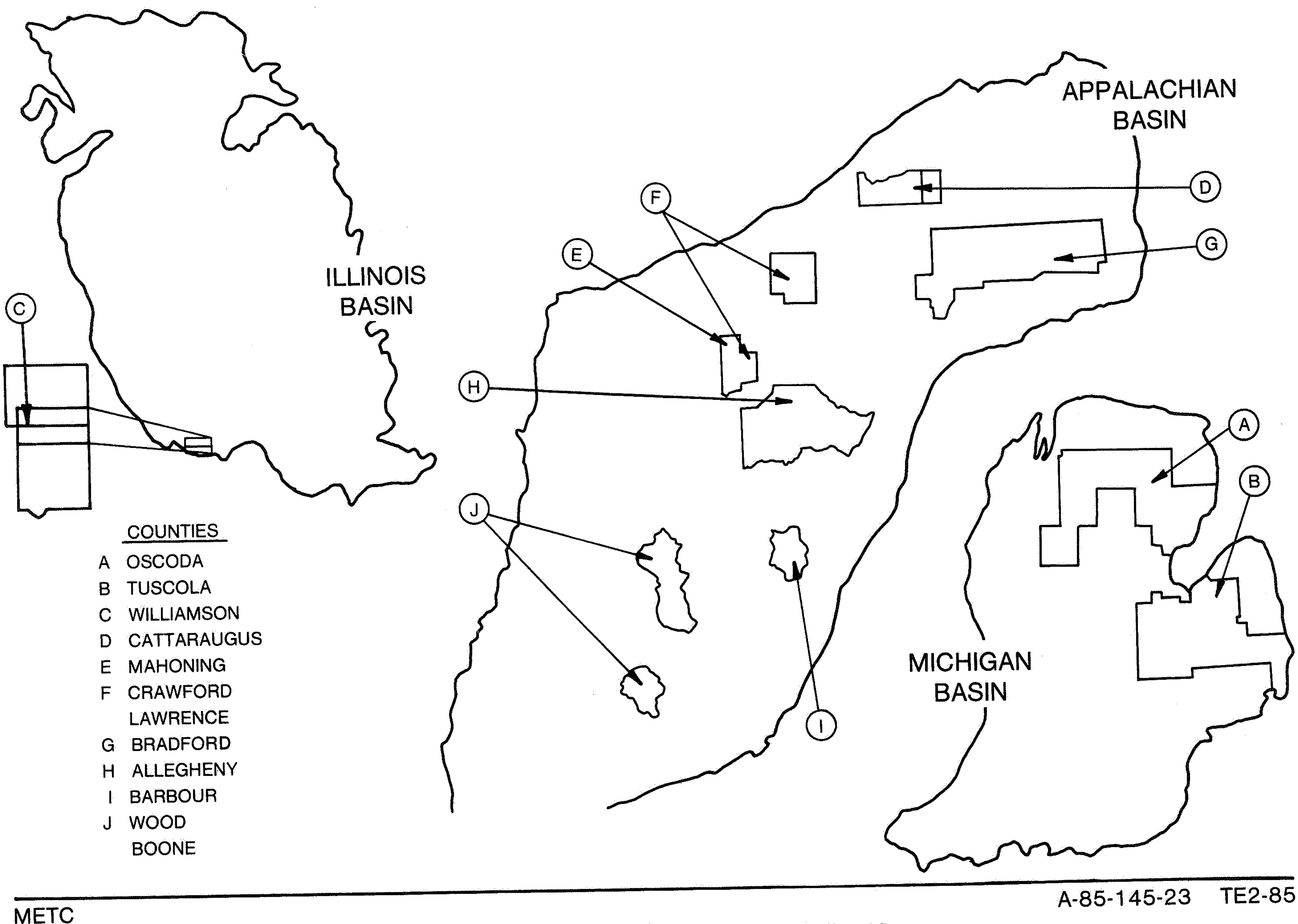
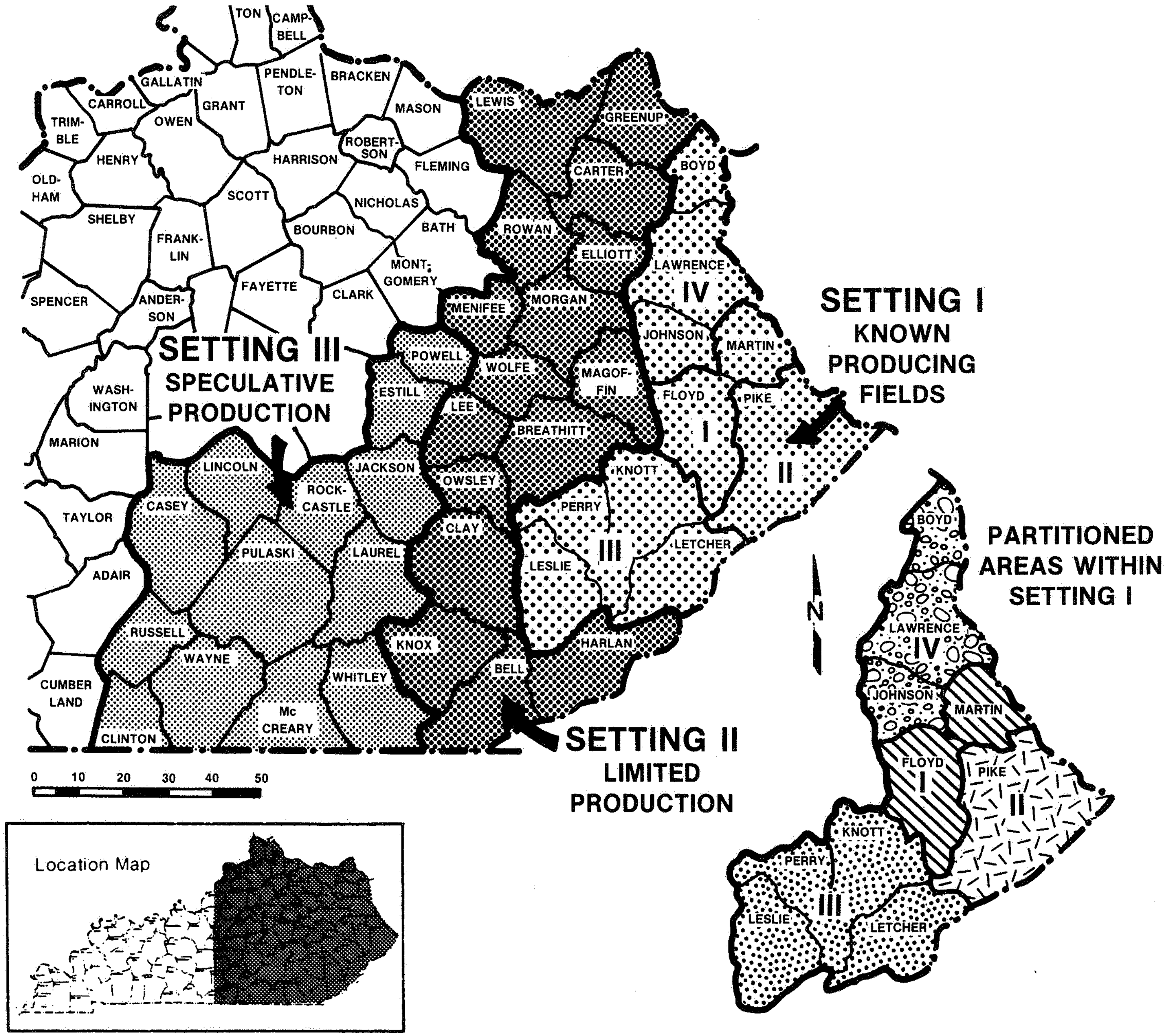


FIGURE 4. TARGETED AREAS FOR NEW TEST WELLS



Prepared By: Lewin and Associates, Inc., 1985.

A-86-115

FIGURE 5. GEOLOGICAL SETTINGS FOR DEVONIAN SHALES OF KENTUCKY

and Cleveland shales show increasing radioactivity as the shales thin and become shallower moving westward. The Devonian shale outcrop marks the northwest border of the setting. This setting is an extension of the Big Sandy Field and has very little historical Devonian shale gas production. Only recently have commercial quantities of gas been found in some of the counties. The recent activity in Breathitt, Harlan, Morgan, and Knott counties, and the geological data known at present, make this extension area of the Big Sandy appear favorable.

- *Geologic Setting III* encompasses the westernmost counties of eastern Kentucky. Data availability and well control data are limited, and the area is categorized as speculative. Only a gas-in-place value has been developed for this portion of the state. The setting is bounded to the west by the Cincinnati Arch and shale outcrops that lie to the north. The Cleveland and lower Huron shales in this setting are very shallow and gradually thin to less than 50 feet in thickness. The only Devonian shale gas production in the area to date has been in the Raccoon Mountain Field of eastern Laurel County.

In addition to the more traditional borehole shooting method, the following three well stimulation techniques were evaluated in this study:

- Small radial stimulation (X_f = 30 feet) (X_f = induced fracture length), which is attainable with emerging technological improvements in omnidirectional stimulation.
- Small vertical fracture (X_f = 150 feet), which is attainable but not yet fully controllable or predictable with current technology.
- Large vertical fracture (X_f = 600 feet), which is potentially attainable with significant advances in technology or alternate fracture fluids and proppants.

The results of the analysis are shown in Table 3.

Four major findings emerged from the assessment of the Devonian gas shales of Kentucky.

1. The Devonian shale gas resource of Kentucky is estimated at about 82 Tcf for the organically rich black shale intervals. Of this, the target areas and intervals appraised in detail contain 36 Tcf.
2. A substantial portion, 9 to 23 Tcf, of natural gas appears to be recoverable from the Devonian shales of Kentucky. The amount of natural gas actually recoverable depends on the completion and stimulation technology employed and the shale sequences that are developed. Of the 9 to 23 Tcf, 9 to 16 Tcf are recoverable from Geological Setting I, the eastern portion of the state and further development of the Big Sandy Field. An additional 3 to 7 Tcf are estimated to be recoverable from the westward extension of the Devonian shale gas pay.
3. A variety of production strategies are required for efficiently recovering the gas-in-place. The Big Sandy area, the historically developed portion of the state (i.e., Floyd, Martin, and Pike counties), has adequate natural fracture permeability (0.1 millidarcy) and fracture intensity (5-foot spacing), which allow acceptable gas recovery efficiencies to be obtained with small-scale stimulation. As drilling progresses northward and westward to the tighter and less densely fractured areas of the Devonian shales, advanced field development, completion, and stimulation technologies will be essential. Here, closer well spacings, rectangular pattern layouts, multiple interval completions, progressively larger volume stimulations, fracturing, and proppant transport technologies will be required to obtain economic gas flow rates.
4. Considerable amounts of additional geological, geophysical, and engineering data are required to properly define and achieve the gas production potential of the Devonian shale. Beyond the conventional gas storage and production mechanisms, numerous other factors, such as fracture permeability and intensity, permeability anisotropy, and adsorbed gas, govern the efficient recovery of Devonian shales. While past work has provided some of these data, a considerable amount of extrapolation and reliance on assumption was required to establish the estimates reported here. In addition, major variations in well performance exist within the same area and county that defy traditional reservoir analyses and vastly heighten the risks of Devonian shale gas development. Substantial future analytical, laboratory, and field research are required to unlock the potential of this vast unconventional gas resource.

4.4.3 The Clinton Sand Study

A geologic and engineering analysis study was completed that aimed at explaining the production

TABLE 3. IN-PLACE AND TECHNICALLY RECOVERABLE GAS FROM DEVONIAN SHALES OF KENTUCKY

			TECHNICALLY RECOVERABLE GAS (in 40 years) (Tcf)			
	TOTAL DRILLABLE AREA (mi^2)	TARGETED GAS-IN-PLACE (Tcf)	BOREHOLE SHOOTING	RADIAL STIMULATION $X_f = 30ft$	SMALL VERTICAL FRACTURE $X_f = 150ft$	LARGE VERTICAL FRACTURE $X_f = 600ft$
1. GEOLOGICAL SETTING I						
Area I	319	5.4	2.5	3.2	3.8	4.4
Area II	474	2.8	1.7	2.0	2.3	2.4
Area III	919	8.1	3.7	4.8	5.5	6.3
Area IV	615	3.2	1.5	2.0	2.4	2.9
Subtotal	2,327	19.5	9.4	12.0	14.0	16.0
2. GEOLOGICAL SETTING II	4,047	17.0	2.6	4.0	5.1	7.2
Subtotal	6,374	36.5	12.0	16.0	19.1	23.2
3. GEOLOGICAL SETTING III[1]	2,324	6.2	—	—	—	—
4. OTHER NON-TARGETED[2] SHALE INTERVALS	—	38.9	—	—	—	—
TOTAL	8,698	81.6	—	—	—	—

[1] Technically recoverable gas is not calculated for this area.

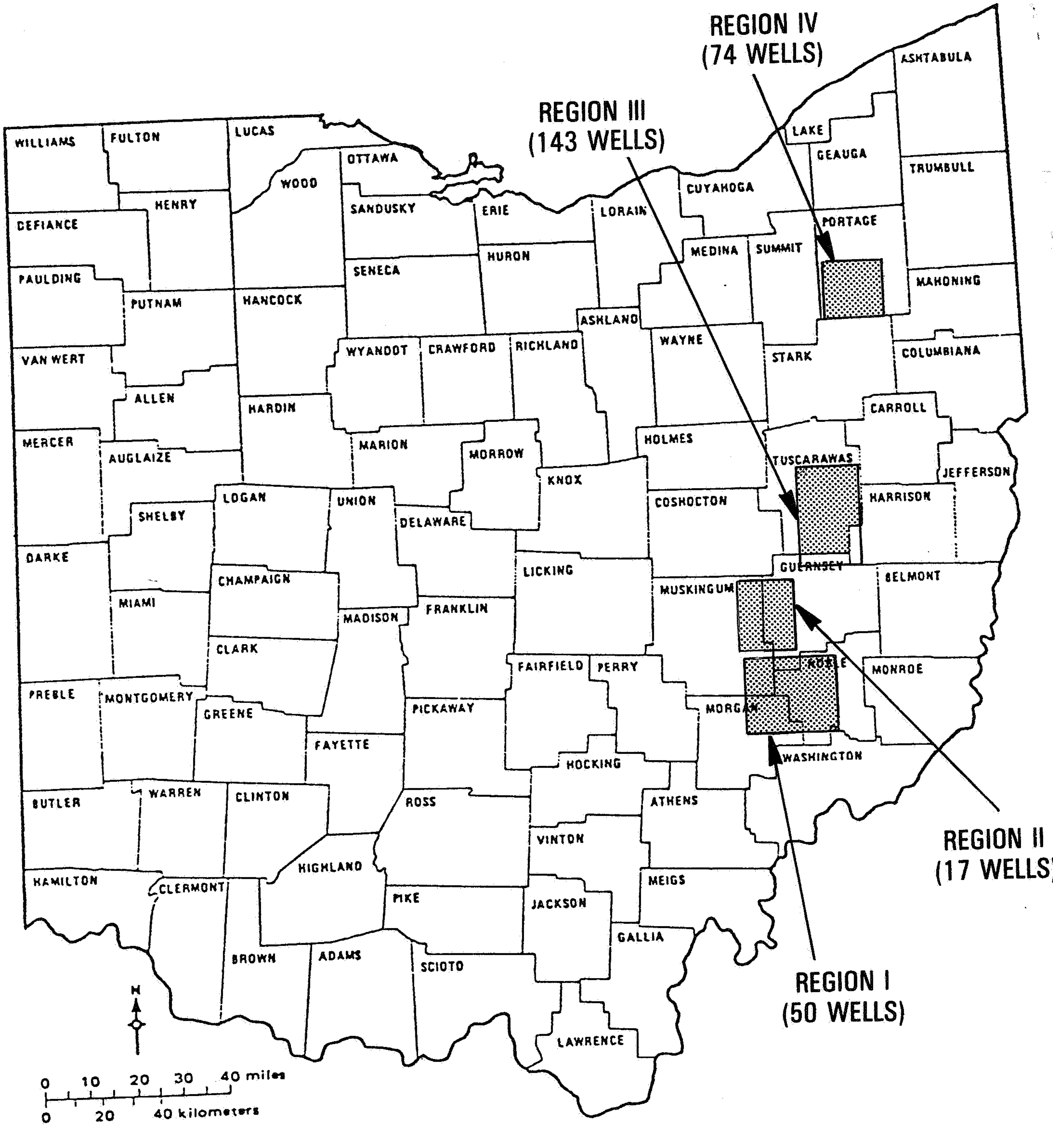
[2] Drillable area for nontargeted shale intervals is included in Geological Settings I-III; technically recoverable gas is not calculated for more target shale intervals.

SOURCE: Lewin and Associates, Inc. (Kuuskrra and others 1985).

performance of Eastern tight sands formations. Logs, completion data, and production performance records were evaluated for a number of Clinton sandstone wells in east central Ohio. The study area was divided into four regions based on well groupings, as shown in Figure 6. The study attempted to (1) recognize the type of productive mechanism (linear vs. radial), (2) predict expected recoveries, and (3) evaluate the size of reservoir and optimum fracture treatments for characteristic areas.

Production data were plotted, and wells were classified as having either linear (≤ 0.6) or radial (> 0.6) slopes. Using the plots and various reservoir parameters calculated from the well logs, a drainage radius and reservoir geometry were determined. Statistical analysis showed that the radial group had a median expected ultimate production of about 50 million cubic feet (MMCF) and the linear group had a median expected ultimate production of about 20 MMCF. Both the radial and linear distributions were polymodal and were divided into low-, transitional-, and high-production segments. Some observations were made about the low- and high-production distributions: the high group included one-half of the wells with greater than 75-percent sand lenses; the low group included only one-fourth of the wells with greater than 75-percent sand; and the fracture treatments were generally quite similar except for four larger stimulation treatments and one small treatment. Three of the four large treatments led to high production wells; the remaining treatment led to a transitional well, using only one-fourth the usual amount of sand. The small treatment led to a low-production well.

Analysis of induced fracture length indicated that larger fracture treatments could have been used to fully extend the induced fracture across the sand body to increase production performance.



A-84-368

FIGURE 6. REGIONS OF CLINTON SAND STUDY AREA

A Society of Petroleum Engineers (SPE) paper entitled "Reservoir Geology of Some Tight Clinton Sandstones, Eastern Ohio" (J. R. Ammer and others 1985) was published as a result of this study. The paper provided industry with a methodology for calculating reservoir parameters, such as size and geometry, which are important in designing stimulations and estimating reserves.

The practical approach used in this study was based on the theory that the line on a log-log plot of cumulative production versus time is indicative of flow behavior from the reservoir to the well. Applying this analysis to wells covering a wide area provides insights to factors affecting recovery. Afterwards, suggestions for improvement can be made, for example, increasing the size of stimulation volumes.

As part of the study, a detailed lineament analysis was conducted for a selected region of the Clinton sand area. The lineament analysis attempted to determine whether any relationships existed between Clinton sands gas well production and lineaments. (Lineaments, believed to be mappable surface manifestations of subsurface fracture zones, are thought to affect production when in close proximity to gas wells.)

The data showed that a statistically significant increase in open flow occurred for those wells that were less than 500 feet from the nearest lineament, as opposed to the amount of open flow for wells that were more than 500 feet from the nearest lineament.

Production data were used to calculate linear and radial drainage distance distributions. These distributions provide insight into the expected Clinton sandstone reservoir sizes. The linear and radial drainage distance distributions were based on production drainage boundaries derived from the breakpoint on the log cumulative production versus log time curves for wells that had breakpoints. The median drainage length for the linear wells is about 500 feet (150 m), while the median drainage radius for the radial wells is more than 2,000 feet (600 m). This shows that the majority of the radial wells definitely are not linear wells that have not sensed their drainage boundaries.

A detailed multivariate statistical analysis was also incorporated into the project. The objectives were to identify the important variables, out of the 51 variables examined, that affect the 60-month cumulative production and the open flow of a well. These variables were then used to develop a statistical rule to help in predicting production, and to help in characterizing the area.

Based upon the analysis of a 60-month cumulative production, 80 percent of the "good" wells were correctly classified, 98 percent of the "average" wells were correctly classified, and 86 percent of the "poor" wells were correctly classified. In total, 94 percent of the wells were correctly classified, based upon the 16 most important variables for a 60-month cumulative production.

Based upon the analysis for open flow, 95 percent of the "good" wells were correctly classified, 74 percent of the "average" wells were correctly classified, and 68 percent of the "bad" wells were correctly classified. A total of 77 percent of the wells were correctly classified, based upon the 18 most important variables for open flow.

This study has given us a better understanding of the factors affecting production in the Clinton sands. It is hoped that this knowledge can be applied to other tight reservoirs and to the Devonian shale. A more complete understanding can lead to improved technology, which could make gas production in the tighter reservoirs more economical.

5.0 REMAINING RESEARCH ACTIVITIES

In the past, activities have been directed at the characterization of the eastern gas shales and the assessment of gas-in-place. More recently, efforts have emphasized the understanding of extraction and production mechanisms and the validation of predictive models for estimating technically recoverable shale gas. This research is described in previous reports on the subject (Morgantown Energy Technology Center February 1985, February 1984). In addition, research reports from all available sources are listed in a bibliography on unconventional gas sources (Komar 1983).

Remaining research will focus on the effects of natural fractures and in situ stresses on shale gas production. The relationship between in situ stress ratios and regional geological structures will be investigated to develop a diagnostic approach to locating areas of intensive natural fracturing. These efforts will provide guidelines for locating regions where induced hydraulic fractures can be applied effectively. In support thereof, computer modeling developments are continuing to provide methodology and software for determining induced fracture geometry, including the effects of in situ stresses and natural fractures.

Research will continue to emphasize improving understanding of the production characteristics of Devonian shale in areas of little or no production. In support of this goal, an offset well test project and reservoir verification tests will be conducted to quantify reservoir properties and their directional nature. The data gathered will provide the basis for estimating technically recoverable shale gas resources for the Appalachian Basin outside Ohio.

A data base for Devonian shale formations in the eastern U.S. is planned to efficiently estimate the potential for shale gas production in each state of the Applalachian Basin underlain by Devonian age shale. DOE will develop a data base for Devonian shales that will allow the development, when the market price and demand warrant it, of new resources.

A study and evaluation of factors affecting the widespread development of Devonian shale oil reservoirs is planned. Emphasis will be on developing appropriate production practices that will reduce problems associated with rapid decline in production from oil shale wells. Laboratory evaluation and screening will provide design considerations for subsequent field testing and evaluation of results.

Research is underway for the development of fracture mapping and downhole reservoir testing tools. This project will design, fabricate, and test a tool for mapping natural and induced fractures downhole, and to design, fabricate, and test a tool that permits rapid production testing and fluids sampling simultaneously under a wide variety of test conditions.

Another area of research is recovery efficiency testing. The research will concentrate on verifying model predictions that indicate improved recovery efficiency from multiple hydraulically fractured horizontal wellbores. Recent advances in directional drilling have resulted in horizontal drilling technology for deep consolidated formations. Also, recent production performance modeling of multiple hydraulic fractures in a horizontal wellbore indicate improved drainage of gas from Devonian shale formations. This new concept needs to be tested as a means for improving the low recovery efficiency of Devonian shale reservoirs by horizontally drilling, coring, logging, and multiple hydraulic fracturing a Devonian shale well to verify the magnitude of improved recovery efficiency.

6.0 ACRONYMS AND ABBREVIATIONS

AHM	Automatic History Matching
DOE	Department of Energy
LLNL	Lawrence Livermore National Laboratory
MCFD	Thousand Cubic Feet Per Day
METC	Morgantown Energy Technology Center
MMCF	Million Cubic Feet
NESC	National Energy Software Center
OSU	Ohio State University
R&D	Research and Development
SAI	Science Applications, Inc.
SPE	Society of Petroleum Engineers
Tcf	Trillion Cubic Feet
TPL	Tailored Pulse Loading
UGR	Unconventional Gas Recovery
USGS	U.S. Geological Survey
WVU	West Virginia University

7.0 REFERENCES

Knutson, C.K., J.R. Ammer, and A.B. Yost, II. 1985. Reservoir Geology of Some Tight Clinton Sandstones, Eastern Ohio. SPE Paper No. 13853.

Komar, C.A. May 1983. Unconventional Gas Resources: Available Publications Listing. DOE/MC/19239-1295. NTIS/DE83012852. 163 p.

Kuuskraa, V.A., K.B. Sedwick, K.B. Thompson, and D.E. Wicks. May 1985. Technically Recoverable Devonian Shale Gas in Kentucky. DOE/MC/19239-1834. NTIS/DE85008608. 120 p.

Morgantown Energy Technology Center. February 1985. Eastern Gas Shales Topical Report. DOE/METC/SP-216. NTIS/DE85001983. 16 p.

Morgantown Energy Technology Center. February 1984. Eastern Gas Shales Subprogram Topical Report. DOE/METC/SP-207. NTIS/DE84011991. 17 p.

Natural Petroleum Council. 1980. Unconventional Gas Sources, Volume I, Executive Summary. Washington, D.C. 51 p.

Swift, R.P. 1984. A Perspective on Modeling Tailored-Pulse Loading (TPL) for Borehole Stimulation. Livermore, California: Lawrence Livermore National Laboratory. UCID-20147. NTIS/DE84016203.