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QUANTITATIVE ANALYSIS OF THE ECONOMICALLY
RECOVERABLE RESOURCE

By

C. V. Pulle and A. P. Seskus

May 1981

Prepared for

UNITED STATES DEPARTMENT OF ENERGY
Morgantown Energy Technology Center
Morgantown, West Virginia

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SUMMARY

The objective of this study is to obtain estimates of the economically recoverable gas in the Appalachian Basin. The estimates were obtained in terms of a probability distribution, which quantifies the inherent uncertainty associated with estimates where geologic and production uncertainties prevail. It is established that well productivity on a county and regional basis is lognormally distributed, and the total recoverable gas is Normally distributed. The expected (mean), total economically recoverable gas is 20.2 trillion cubic feet (TCF) with a standard deviation of 1.6 TCF, conditional on the use of shooting technology on 160-acre well-spacing. From properties of the Normal distribution, it is seen that a 95 percent probability exists for the total recoverable gas to lie between 17.06 and 23.34 TCF.

The estimates are sensitive to well spacings and the technology applied to a particular geologic environment. It is observed that with smaller well spacings--for example, at 80 acres--the estimate is substantially increased, and that advanced technology, such as foam fracturing, has the potential of significantly increasing gas recovery. However, the threshold and optimum conditions governing advanced exploitation technology, based on well spacing and other parameters, were not analyzed in this study. Their technological impact on gas recovery is mentioned in the text where relevant; and on the basis of a rough projection an additional 10 TCF could be expected with the use of foam fracturing on wells with initial open flows lower than 300 MCFD. From the exploration point of view, the lognormal distribution of well productivity suggests that even in smaller areas, such as a county basis, intense exploration might be appropriate. This is evident from the small tail probabilities of the lognormal distribution, which represent the small number of wells with relatively very high productivity.

1.0 INTRODUCTION

A key objective of the U.S. Department of Energy's (DOE) Eastern Gas Shales Project (EGSP) is: "Develop accurate estimates of gas-in-place and economically recoverable resources". The objective of this study is to obtain probabilistic interval estimates of the economically recoverable gas from Devonian shale. The scope of the study is confined to the Appalachian Basin and the use of "shooting" technology as the recovery mode. It is clear that the economics of gas recovery in the context of Devonian shale is primarily a function of the site-specific geology and the stimulation technique to be used. The geology as it relates to the Appalachian Basin, the area under investigation in this study, Figure 1, is fairly well characterized. An overview of reservoir-geologic characteristics and the treatment of specific geologic areas are contained in Sections 2 and 3.

As for recovery technology, the historical but well established "shooting" technology is considered. In shooting, the targeted shale section is treated, or shot, with explosives. Usually, 10 pounds of 80-percent nitroglycerin is applied to each foot of shale section. Shooting, for example, 1000 feet of shale section could cost between \$5,000 and \$10,000, in comparison to a cost of \$10,000 to \$20,000 for a waterfrac stimulation. Apart from the classical shooting stimulation, promising new hydraulic technology being developed in the EGSP, such as "foam fracturing" (1) has shown a significant superiority over shooting. In some instances, more than a 100 percent increase in production rates of wells with low open-flow rates (50-100 MCFD) has been observed over shooting open-flow rates. The significance of foam fracturing is briefly discussed in Sections 2 and 4, but a detailed analysis of this technology as it affects the economically recoverable resource is outside the scope of this study. As a larger data base on foam fracturing technology and other emerging technology, such as tailored-pulse-loading, is established, a similar study that incorporates these technologies will be needed.

Section 2 provides an "Exploration and Exploitation Overview" which contains a discussion of the geologic and reservoir parameters as these affect gas

Figure 1: Study Area

recovery. Section 3 contains the technical approach and analysis adopted for this study, and Section 4 provides an interpretation of the results and conclusions.

A brief background and rationale for this study are discussed next.

1.1 BACKGROUND AND RATIONALE

It is reckoned that the first shale well was drilled in Fredonia, Chautauqua County, New York, in 1820. By 1975, 155 years later, approximately 10,000 producing shale wells in West Virginia, Kentucky, Virginia, and Ohio were known to exist. Most prolific of all are the Big Sandy (eastern Kentucky) and Cottageville fields where most of the production from the basin has occurred. Producers have consisted of utilities, large and small independent operators, and "self-help" consumers. In the Big Sandy field there has been over 60 years of drilling experience, and producing wells of 75 years or more have existed in the Appalachian Basin.

In one study (2) it was noted that 40 percent of wells had no gas flow, but after fracturing a typical production rate (50-200 MCFD) occurred, leaving 11 percent of wells which were considered dry holes. Typical well lifespans have exceeded 30 years, and although several wells with low production rates have previously been considered marginal because of regulated prices and inflation, current market prices (up to \$4.50 for Devonian shale gas) have made extraction of gas from shale economically attractive. This is reflected in the intense drilling activity in Appalachia and elsewhere since partial deregulation of gas prices. For "self-help" consumers such as colleges and schools, hospitals and religious institutions, and small industry with only modest power and heating needs, the shale well with its typically long production span is a dependable long-term source of energy when compared to the alternative of rising energy costs and possible gas curtailments in the future.

About 200,000 square miles ($\approx 322,000$ sq kilometers) of the Appalachian Basin are known to contain gas-bearing Devonian shale. The mean gas content of the shale varies from 0.003 to 1.11 cubic feet of gas per cubic foot of shale with a total gas-in-place estimate ranging from 277 to 900 TCF (3). The economically recoverable gas from shale has been calculated to range from 10 to 520 TCF (3).

These estimates are based on offgas, volumetric, and standard production

decline curve data. Volumetric calculations based on a small number of spatially disparate sample points with gas content arithmetically averaged over nonuniform stratigraphic horizons could lead to gross estimates. Use of production decline curves to estimate recoverable gas may also result in gross estimates depending on the relative characterization of single and dual porosity systems, and the use of open flows as a reliable and consistent indicator of well productivity. There is evidence (4) to show that both single and dual porosity-like systems separately characterized by different production decline curves exist for the shale, and that open flows are not always a true indicator of long-term well productivity.

This study employs a scientific, rigorous approach, using actual cumulative production data, to make statistical inferences about the recoverable gas. Admittedly, like all methods of estimation, this study too has its own set of assumptions and limitations. However, it will provide a basis for quantifying the uncertainty associated with interval estimates by means of a probability distribution. Other wide-ranging interval estimates have not been supported by a systematic quantification of the uncertainty associated with these estimates.

Accurate estimates of the economically recoverable gas are required for various reasons. First, future exploitation in terms of field development in meeting gas demand will depend on how much gas is economically recoverable. In the case of Devonian shale gas, the economics of field development is already enhanced by existing infrastructure such as pipeline networks, Figure 2. Second, investment in RD&D in new technology to increase the supply base will be influenced by what can or cannot be recovered by current technology. It is estimated, for instance, that less than 10 percent of the gas-in-place is recovered for a 20-year period (5). Third, national, regional, and local energy planning require estimates of supply.

Location of Devonian Shale Formations with Major Natural Gas Pipelines
(Source: The Oil and Gas Journal, The Petroleum Publishing Company)

2.0 EXPLORATION AND EXPLOITATION OVERVIEW

The economically recoverable gas from shale is to a large extent constrained by geologic and reservoir factors. The shales are known to possess relatively low shale-matrix and fracture porosities (0.4 to 7 percent), permeabilities (< 0.1 millidarcies) and rock pressures (currently about 500 PSI). Production generally occurs in geologic areas where natural fractures are present. Exploration concepts such as the stress-ratio factor to detect fracture intensity are being developed and tested.

Offgassing experiments have indicated substantial amounts of gas trapped in the pores of the organic rich shale matrix. Gas-in-place is estimated to range from 277 to 900 TCF. However, much of this gas remains trapped and cannot be recovered by present state-of-the-art technology. Reservoir capacity of the shales is largely a measure of fracture capacity. Initially, it is believed that most of the gas produced flows to the wellbore from gas in fractures. Production decline curves exhibit two distinct types of gas flow (4). There is the purely exponential decline which tends to support single-porosity behavior and the hyperbolic form that supports a dual-porosity system. Both systems are governed by the generally low production rates (50-200 MCFD) over long production timespans (20 years or more).

In the case of the hyperbolic form more recoverable gas can be expected in the long run; how much gas seems to depend on time only as witnessed by a number of wells that have produced for more than 50 years, and are still producing. It therefore appears plausible that in the hyperbolic case, the gas produced in the long run, which is a steady-state rate, is desorbed from the fracture surface to the fractures, notwithstanding relatively low desorption and diffusion rates. It follows, then, that fracture surface area is just as important as fracture density. Where fracture density is low, increasing fracture surface area could enhance gas volume.

Shooting is known to create small induced fractures. But existing surface area within the fracture system may not be significantly increased. In fact, shooting might cause some healing of fractures and some degree of skin damage.

On the other hand, foam fracturing could not only create fracture growth but maintain or, perhaps, increase fracture surface area by efficient propping agents. With minimum adverse effects expected from fluid loss through leakage and fluid-shale interactions, recoverable gas is enhanced with foam fracturing treatments (1).

Recoverable gas depends on the number of wells drilled which, in turn, depends on well spacing in a particular geologic region. Well spacing, usually measured in terms of acreage, provides a measure of the areal drainage of a reservoir around a well. Well spacing is roughly uniform and constant for isotropic reservoirs. However, in the context of an anisotropic reservoir characterized by natural fractures, well spacing is difficult to define. This is because the density, orientation, and spatial configuration of fractures are not well known. Apart from these considerations upon which well spacing will depend, there is also the question of induced (through stimulation) fracture lengths which could influence well spacing. These questions are currently being addressed in the EGSP. Also, concepts such as the stress-ratio factor are being tested, and preliminary indications are that stress-ratio might provide a valuable exploration tool in detecting fracture intensity.

For this study, a well spacing of 160 acres is used, which is not different from historical well spacing data for the shale. However, recoverable gas is also estimated for reduced spacings. It appears that these estimates could be significantly improved as a result of EGSP RD&D advances in exploration and exploitation.

The next section discusses the technical approach and the method of analysis used to obtain probabilistic interval estimates of the recoverable gas using shooting stimulation technology.

3.0 TECHNICAL APPROACH AND ANALYSIS

This section contains a discussion of the technical approach and analysis for obtaining the economically recoverable resource. A pictorial outline of the steps involved in the approach and analysis is shown in Figure 3. A brief description of the work associated with each step follows.

3.1 DATA COLLECTION AND COMPILATION

Cumulative production data, with initial open flows (IOF's) and initial rock pressures (IRP's) for 1780 shale wells were obtained. Use of the data is restricted because of proprietary considerations. The data are for the States of Kentucky, Ohio, West Virginia, and Virginia. Data on selected geological variables such as radioactive shale thickness, conodont alteration index (CAI), drilling depth, and stress ratio were collected from various published sources and compiled for use in the study. Data for these geological variables are contained in Appendix A.

3.2 INITIAL SCREENING AND DATA EVALUATION

The 1780 shale wells consist of "active" and "abandoned" wells. Some wells were abandoned after a few years due to mechanical problems or insignificant production. Recorded production of wells ranged from a few years to over 50 years for some wells. After screening the list of active and abandoned wells, it was decided to select only those wells with 10 years or more of production history. This was necessary to ensure a large enough sample size for purposes of data reduction, especially in terms of actual and potential well productivity.

As a result of this screening and evaluation, the original sample size of 1780 wells was reduced to 1534 wells. Screening and evaluation for the following counties for each of the states was made.

Figure 3: Work Flow Outline

Kentucky:	Floyd, Johnson, Knott, Lawrence, Letcher, Martin, Pike, Holmes
Ohio:	Lawrence, Licking, Meigs, Morgan
Virginia:	Buchanan
West Virginia:	Boone, Cabell, Jackson, Kanawha, Lincoln, Logan, Mingo, Putnam, Roane, Wayne, Wood

During this phase of the study, a region nearly corresponding to the Appalachian Basin was selected for estimating its recoverable gas potential. The region is shown in Figure 1, cited earlier in the report, and also contains that portion of the region for which production data were obtained. The selection of this particular region was based on the availability of production and geologic data.

3.3 DATA REDUCTION

In this phase of the study, basic summary statistics were computed using the production data. The data was used to construct initial histograms, and statistical measures such as the means, variances, coefficients of variation, minimum-maximum observations for various counties with production data were obtained. The initial histograms provided the first indication of how well productivity is distributed, and the relative productivity of each county. These histograms were then progressively "fine-tuned" in search of an underlying distribution that could serve as a model of the state-of-nature as it relates to gas recovery from the shales.

The next subsection deals with the extension of this preliminary effort in data reduction, and provides the details of the distribution analysis. Raw geologic data was also used to construct some maps, such as the stress-ratio map, which are referred to in various sections of the report.

3.4 DISTRIBUTION ANALYSIS

The general results of the distribution analysis for states and most counties are shown in Appendices B (Histogram Plots) and C (Significance Tests). A summary of productivity characteristics appears with each histogram, where applicable. These characteristics refer to both production and geologic observations. Associated with each county, the mean radioactive shale thickness (MRST), the conodont alteration index (CAI) which is a measure of thermal

maturity, the stress ratio, and depth are provided. It is estimated that these measures affect well productivity. Also, the mean, the minimum-maximum observations as a measure of dispersion, and sample size for each histogram are given.

It is observed that almost all the distributions exhibit a skewness to the left with a tail to the right. In particular, Figure 4, which is the general distribution for all states, a lognormal distribution appears to be a remarkably good model for characterizing well productivity. This is confirmed in the test of significance shown in Figure 5 by the nearly straight line probability plot.

As the sample size increases, there appears to be a strong tendency towards the lognormal form, as seen in the distributions of some counties. This consistent appearance of the lognormal tendency reveals a stable underlying distribution of well productivity, which is significant in terms of future exploration.

First, it is clear that in drilling for gas it is more probable to find more wells with low productivity as represented by the left part (higher density) of the distribution than wells with relatively higher productivity which have a smaller probability of occurrence, as represented in the right tail of the distribution. Second, it can be inferred that even in relatively small areas, such as counties, intense exploration is needed to find higher productivity wells having smaller probabilities of occurrence, as represented by the lognormal characterization for some counties. Further details are stated in Section 4.

Also, use of the computed means and variances of lognormal forms is made to calculate the recoverable gas in subsection 3.6. The next subsection discusses the methodology employed in the extrapolation from "training" to "target" areas of the basin. In the so-called "training" areas, production and key geologic parameters are known, while in "target" areas only geologic attributes are known. The cluster analysis discussed in the next subsection illustrates the basis for this extrapolation.

3.5 CLUSTER ANALYSIS

Since production data were only available for portions of the Appalachian Basin, a method of extrapolating to other areas was needed. The approach taken was to first group counties on the basis of their geological similarity, and then assume the distribution of production per well would be the same for all wells drilled anywhere in a group.

FREQUENCY

KENTUCKY, OHIO, WEST VIRGINIA, VIRGINIA PRODUCTIVITY CHARACTERISTICS

MIN : 1.7 MMCF
MAX : 3748 MMCF
MEAN : 404 MMCF
N : 1534

LOGNORMAL DISTRIBUTION

$$f_X(x) = \frac{1}{x\sigma\sqrt{2\pi}} \exp \left[\frac{-1}{2\sigma^2} (\log_e x - \mu)^2 \right]$$

Figure 4: Histogram for States

Figure 5: Probability Plot (Kentucky, Ohio, West Virginia, Virginia)

For groups containing producing wells, the parameters of the distribution were estimated from the sample; for other groups, the Delphi method was used to obtain subjective estimates of the parameters. Details of the grouping of the counties, using a statistical technique called Cluster Analysis, are provided in this subsection following certain considerations in the use of particular geologic variables.

The only geological variables available for most counties of the Appalachian Basin are:

- a. Radioactive shale thickness (RST)
- b. Conodont Alteration Index (CAI)
- c. Drilling depth

Other variables were available only for 20 wells in the Appalachian Basin (to be increased to 39 at the end of FY80, spread over 28 counties), and so could not be used in time for this study.

The EGSP has shown that the radioactive shales are organically richer and higher in gas content than the nonradioactive shales (7). The radioactive shales are also basically the black or brown shales which provide the majority of Devonian Shale gas production. Ray (2) has estimated that the brown shale produced 60 percent of the cumulative production from the Eastern Kentucky Field.

No definitive relationship has been established between radioactive shale thickness and gas production. However, the National Petroleum Council (NPC), in their study of Devonian shales (8), found correlations between RST and initial open flows, and between initial open flow and cumulative production.

Based on the above, radioactive shale thickness was included as one of the parameters to be used in this study. Since there was no consistent set of readily available RST maps covering the Appalachian Basin the values determined in the NPC study (8) were used.

Thermal maturity (of which CAI is a measure) has also been found to be significantly related to gas content in Devonian shale cores (9). Although vitrinite reflectance is a more accurate measure of thermal maturity, it was not available over as wide an area as CAI, and so CAI was chosen for use here. The values were obtained from a map prepared by the United States Geological Survey (USGS) (10).

The drilling depth (from the surface to the base of the Devonian shale) was also included in the analysis for completeness, since it could be

removed from the analysis if initial results indicated it was not necessary. The average value for each county was obtained from the NPC study.

It was felt that it would be useful to incorporate some parameter that could possibly be related to the presence of natural fractures or ease of producing induced fractures. One parameter that has been proposed as having these properties is stress ratio (the ratio of minimum horizontal stress to vertical stress) (6). Although the stress ratio for Devonian shale has only been experimentally determined for a small number of counties, a relationship between stress ratio and treatment depth was determined by McKetta of Columbia Gas (6). By using this relationship with the drilling depths above, predicted values of stress ratio for each county in the study area were determined. These values generally agreed with the actual ones given by Komar (1), the main difference being in Trumbull County, Ohio.

Figure 6 shows the calculated values in three categories: 0.4 to 0.7; 0.7 to 1.0; and greater than 1.0. The lowest values are postulated as those most favorable to gas production. The above four variables were then used in the Cluster Analysis, as described below.

Cluster Analysis is a statistical technique for identifying groupings or clusterings of objects under study that best reflect certain empirically measured relations of similarity (11). This technique has been applied previously in the oil and gas industry by Gess and Bois (12). The first step in conducting a Cluster Analysis is to obtain a measure of the similarity between each pair of objects (counties, in this case). An example of the calculation is given below, followed by the general formula.

Let i, j, k, m, n be five counties, with the following values of RST.

<u>County</u>	<u>RST (feet)</u>
i	300
j	200
k	300
m	50
n	500

For RST considered alone, the following diagram depicts the situation graphically:

Figure 6: Stress Ratio Map of the Appalachian Basin

The similarity between two counties based on RST is defined as

$$1 - \frac{RST_2 - RST_1}{RST(MAX) - RST(MIN)}$$

For counties i and j, the similarity is

$$1 - \frac{200 - 100}{500 - 50} = .78$$

For counties j and k, the similarity is

$$1 - \frac{300 - 200}{500 - 50} = .78$$

While, for counties m and n, the similarity is 0.

The general formula for this case is

$$S_{ij} = 1 - \frac{X_i - X_j}{R}$$

where X_i and X_j are the RST values for counties i and j, and R is the range of RST values in the sample. These values are normalized, varying between 0 and 1.

In order to extend this definition to include several parameters, the method that is used is to calculate the weighted average (using weights specified in some manner) of the similarity values of individual parameters. If X_{ik} is the value of geological parameter k for county i, then the general definition of similarity used is

$$S_{ij} = 1 - d_{ij}$$

$$d_{ij} = \frac{\sum_k w_k^2 \frac{(X_{ik} - X_{jk})^2}{R_k^2}}{\sum_k w_k^2}$$

where w_k is the relative weight of parameter k, R_k is the range of parameter k.

This definition can be interpreted as defining an ellipse centered on point i, such that all points on the surface of the ellipse have the same

similarity with point i . For $k = n$ this concept is extended to n dimensions.

The matrix of values S_{ij} (or d_{ij}) is then input to a statistical package which performs the cluster analysis. Essentially, this consists of finding "neighborhoods" in the n -dimensional space of the n geological parameters; i.e., similar counties are ones that are close together in this n -space.

Example:

Consider the distance matrix

	1	2	3	4	5	6
1	0	.31	.23	.31	.23	.23
2	.31	0	.31	.23	.31	.31
3	.23	.31	0	.31	.04	.07
4	.31	.23	.31	0	.31	.31
5	.23	.31	.04	.31	0	.07
6	.23	.31	.07	.31	.07	0

The cluster map for this matrix is given below.

The cluster map shows the way the units combine as the strength (distance) between them is increased from 0 to 1; i.e., Units 3 and 5 are the most similar, and Unit 6 is more similar to this pair than any other pair of units are to one another.

The data were analyzed for several choices of the relative weights, and also eliminating one parameter at a time, to determine the effect of each parameter. In general, seven clusters were sufficient to produce a high degree of similarity (90 percent) within each cluster. While there were

differences in the individual runs, there was a common basic structure that recurred. Figure 7 shows the final result, based on first extracting the common structure, and then subjectively allocating counties that were placed in different clusters on each run into one of the invariant clusters.

The geologic parameter values of the ten clusters that resulted are given in Appendix A, which also gives the mean values of each parameter for each cluster (NOTE: The RST values are only given for the cluster as a whole, since the NPC requested that their RST value be held confidential at the county level).

Of the ten clusters, five contain at least one county for which production data exists. Table 1 summarizes the geological data, production data, and drillable areas (based on Reference 8). Figures 8 through 17 show each cluster, together with the distribution of mean production per well for that cluster, where applicable. In addition, a geologic summary is given for each cluster.

FIGURE 7: DIVISION OF APPALACHIAN BASIN INTO 10 CLUSTERS

Table 1: Cluster Attributes

Cluster	Drillable Area (sq. mi.)	Radioactive Shale Thickness (feet)	Drilling Depth (feet)	CAI	Stress Ratio	Cumulative		Production Coefficient of Variation	Number of Wells
						Mean	Standard Deviation		
1	3536	332	3700	1.76	0.53	415	390	.94	1436
2	3236	233	5700	2.00	.76	401	266	.66	29
3	4979	146	3200	1.00	.56	261	282	1.08	31
4	8853	103	4100	1.72	.53	114	48	.42	19
5	7435	185	1600	1.04	.94	108	85	.79	19
6	4530	58	900	1.33	1.00				
7	1863	41	1400	2.30	.97				
8	2859	71	4650	2.50	.54				
9	6545	82	7400	2.36	1.00				
10	9867	77	6900	1.75	1.00				
TOTAL: 53,335									

Geologic Summary (Cluster 1)

Cluster 1 is comprised of eight counties in southwestern West Virginia and 13 counties in eastern Kentucky. This region includes the "Big Sandy" or "Eastern Kentucky" Gas Field and 27 named gas fields in southwestern West Virginia, of which the "Cottageville" is the most productive. The main gas-producing strata within the Devonian shale sequence in this area are the massive black radioactive shales of the Lower Huron Member of the Ohio Shale and the Rhinestreet Member of the West Falls Formation. These units thicken to the east over the entire area.

Fracture occurrence in the Devonian shales is extremely high for the area designated as Cluster 1, due primarily to their association with local and regional geologic structures. Both the Lower Huron Shale and the Rhinestreet Shale have a high density of natural fractures, associated with a mean stress ratio value of 0.53 for the area. The single most important geologic structure controlling Devonian shale gas production is the basement feature known as the Rome Trough. Subsurface stratigraphic data indicate that although the Trough formed during Lower Cambrian time, it influenced sedimentation during deposition of the Devonian system. Recurrent movement along the border faults of the Rome Trough appears to have created some highly fractured reservoirs in the Devonian black shale.

The success ratio for Devonian shale gas wells drilled in this region has been quite high, averaging about 90 percent. Furthermore, wells are reasonably shallow, having an average depth of about 3700 feet. Aggregate radioactive Devonian shale thicknesses are high throughout this area, ranging from 220 to nearly 500 feet, with an average thickness of about 330 feet. The conodont color alteration index (CAI) for this portion of the Appalachian Basin averages about 1.75. Vitrinite reflectance (Ro) values range from about 0.5 to slightly more than 1.0 (the value representing optimum thermal maturity).

Figure 8: Cluster 1 and Histogram of Cumulative Production Per Well (MCF)

Geologic Summary (Cluster 2)

Cluster 2 contains seven counties in western and southern West Virginia and six counties in southwest Virginia. The primary Devonian shale gas-producing unit in this area is the radioactive black shale of the Lower Huron Member of the Ohio Shale. Other producing strata include the Rhinestreet Shale Member of the West Falls Formation and, to a lesser extent, the Marcellus Shale of the Hamilton Group. The Devonian shale sequence thickens in an eastwardly direction over the area.

Two major geologic structures occur adjacent to and within the region of Cluster 2. The basement feature (graben) known as the Rome Trough appears to have exerted considerable influence on the Devonian shales in Wood, Wirt, Roane, Kanawha, and possibly Boone Counties, West Virginia. Recurrent movement along the border faults of the Rome Trough has resulted in some highly fractured reservoirs in the Devonian black shales. Fractures occurring in the six counties in Virginia are most probably related to the Pine Mountain Overthrust Fault and other associated thrust faults recognized in the area.

The average stress ratio value for this region is 0.76, indicating a moderate amount of naturally-occurring fractures within the Devonian shales. Drilling depths are moderate to relatively deep, averaging slightly less than 5700 feet. Cumulative radioactive black shale thicknesses, which average about 235 feet, are favorable for gas production. The conodont color alteration index (CAI) averages about 2.0 for this region of the Appalachian Basin. Vitrinite reflectance (R_o) values range from about 1.0 (the value representing optimum thermal maturity) to 1.5.

Geologic Summary (Cluster 3)

Cluster 3 is comprised of 12 counties in Ohio, three counties in West Virginia, one county in Kentucky, and one county in New York. The major gas-producing black radioactive Devonian shales in order of importance are the Lower Huron of the Ohio Shale, the Rhinestreet of the West Falls Formation, the Cleveland of the Ohio Shale, and the Marcellus of the Hamilton Group. Throughout most of this area the Devonian shale sequence dips and thickens to the east and southeast.

The Devonian shales in this region have a high natural fracture density, as evidenced by the mean stress ratio value of 0.56. The Cambridge Arch is a structural feature that extends through east-central Ohio from southeast to northwest. A decollement and associated fracturing along the Arch may provide the permeability for gas production from the shales. A few counties within Cluster 3 are in close proximity to the Rome Trough, a basement (graben) feature of Lower Cambrian age. Recurrent movement along the border faults associated with the Trough appears to have resulted in some highly fractured Devonian black shale reservoirs. Additional geologic phenomena which may influence Devonian shale gas production in this region are two cross-strike structural discontinuities in eastern West Virginia known as the Petersburg and Parsons lineaments. These structures are thought to be the surface expressions of large volumes of highly fractured rock.

Aggregate radioactive Devonian shale thicknesses are moderate throughout this area, ranging from 69 to 220 feet, with an average thickness of about 145 feet. Drilling depths are relatively shallow, having an average depth of 3240 feet. The conodont color alteration index (CAI) for this portion of the Appalachian Basin averages 1.0. Vitrinite reflectance (Ro) values are generally less than 1.0 (the value representing optimum thermal maturity).

Figure 10: Cluster 3 and Histogram of Cumulative Production Per Well (MCF)

Geologic Summary (Cluster 4)

Cluster 4 consists of 11 counties in eastern Ohio, eight counties in northwestern Pennsylvania, four counties in northern and eastern West Virginia, three counties in southeastern Kentucky, two counties in southwestern New York, one county in western Maryland, and one county in northeastern Tennessee. The major gas-producing black radioactive Devonian shales are the Lower Huron (Dunkirk) of the Ohio Shale, the Rhinestreet of the West Falls Formation, and the Marcellus of the Hamilton Group. Throughout most of this area the Devonian shale sequence dips and thickens to the east and southeast.

The Devonian shales in this region have a high natural fracture density, as evidenced by the mean stress ratio value of 0.53. The Cambridge Arch is a structural feature trending from southeast to northwest through east-central Ohio. A decollement and associated fracturing along the Arch may provide the permeability for gas production from the shales.

Aggregate shale thicknesses are relatively low throughout this region, ranging from 50 to 165 feet, with an average thickness of about 105 feet. Drilling depths are fairly shallow to moderate, having an average depth of about 4100 feet. The conodont color alteration index (CAI) for this section of the Appalachian Basin averages 1.75. Vitrinite reflectance (R_o) values generally range from 1.0 (the value representing optimum thermal maturity) to 2.0.

Geologic Summary (Cluster 5)

Cluster 5 is comprised of 26 counties in northern and east-central Ohio, five counties in northeastern Kentucky, one county in northwestern Pennsylvania, and one county in southwestern New York. The major gas-producing black radioactive Devonian shales in order of importance in this area are the Lower Huron (Dunkirk) of the Ohio Shale, the Rhinestreet of the West Falls Formation, and the Cleveland Member of the Ohio Shale. Throughout most of this region the Devonian shale interval dips and thickens to the east and southeast.

The Findlay Arch in western Ohio appears to be the prominent structural feature that influenced the formation of the Devonian shales to the east. The Cambridge Arch extends from southeast to northwest in eastern Ohio. A decollement and associated fracturing along this structural feature may provide increased permeability for gas production from the Devonian shales. A third geologic structure influencing Devonian shale gas production is the basement feature (graben) known as the Rome Trough. Recurrent movement along the border faults of the Rome Trough appears to have created some highly fractured reservoirs in the Devonian black shale. Fracturing has also been created in the area adjacent to Lake Erie by glacial off-loading along the shoreline.

Despite the presence of the aforementioned geologic structures, the occurrence of natural fracturing in the Devonian shales in Cluster 5 appears to be low, as evidenced by the mean stress ratio value of 0.94. Aggregate radioactive shale thicknesses are moderate, averaging about 185 feet for this area. Drilling depths are extremely shallow for this region, ranging from 500 to 2100 feet and being an average depth of about 1600 feet. Gas production from most of these shallow wells is usually low. However, production is sustained for long periods of time, sometimes exceeding 50 years. The conodont color alteration index (CAI) for this portion of the Appalachian Basin averages about 1.0. Vitrinite reflectance (Ro) values are generally less than 1.0 (the value representing optimum thermal maturity).

Figure 12: Cluster 5 and Histogram of Cumulative Production Per Well (MCF)

Geologic Summary (Cluster 6)

Cluster 6 consists of 14 counties in southeastern Kentucky and six counties in northeastern Tennessee. The major gas-producing black radioactive Devonian shales in this region are the Sunbury-Cleveland and Lower Huron Members of the Ohio Shale.

Devonian shale gas production in this area has been influenced by three major geologic structural features. The Cincinnati Arch and associated faulting is located on the western boundary of this area. Extensions of faulting associated with the Rome Trough have affected the northern half of the Cluster 6 area. The southeastern section of this area has been influenced by faulting from the Pine Mountain Overthrust Belt. Each of these geologic structures may have influenced Devonian shale gas production by creating some highly fractured reservoirs in the Devonian shale sequence.

A high occurrence of natural fracturing is not indicated, however, by the mean stress ratio value of 1.0 for the area. Aggregate radioactive shale thicknesses are very low, ranging from 21 to 150 feet, with an average of about 60 feet. Drilling depths are very shallow, averaging slightly more than 900 feet. The conodont color alteration index (CAI) for this portion of the Appalachian Basin averages about 1.33. Vitrinite reflectance (Ro) values are generally less than 1.0 (the value representing optimum thermal maturity).

Geologic Summary (Cluster 7)

Cluster 7 consists of five counties in western New York. The major gas-producing black radioactive Devonian shales in order of importance in this area are the Rhinestreet of the West Falls Formation, the Dunkirk of the Perrysburg Formation, the Marcellus of the Hamilton Group, and the Genesee of the Genesee Group. These units generally thicken to the south-southeast.

No major geologic structures appear to have influenced gas production from the Devonian shale sequence within the area of Cluster 7. The occurrence of natural fracturing is low, as indicated by the mean stress ratio value of 0.97. Aggregate radioactive shale thicknesses for this area are very low, averaging only about 40 feet. Drilling depths are very shallow, having an average depth of about 1450 feet. The conodont color alteration index (CAI) for this portion of the Appalachian Basin averages about 2.30. Vitrinite reflectance (R_o) values for this area are generally about 1.0 (the value representing optimum thermal maturity).

Figure 14: Cluster 7

Geologic Summary (Cluster 8)

Cluster 8 is comprised of four counties in southwestern New York, two counties in northern Pennsylvania, and two counties in eastern West Virginia. The only major gas-producing black radioactive Devonian shale in this region is the Marcellus of the Hamilton Group.

No major named geologic structures appear to have influenced gas production from the Devonian shale interval within the area of Cluster 8. However, the entire area is located within the Appalachian Fold Belt, which is highly folded and faulted. The existence of these structures may have contributed to the formation of fractured reservoirs in the Devonian black shales.

Natural fracture occurrence in the Devonian shales is extremely high in this area, as evidenced by the mean stress ratio value of 0.54. Aggregate radioactive shale thicknesses are low, ranging from 41 to 110 feet, with an average of about 70 feet. Drilling depths are moderate, with an average depth of about 4650 feet. The conodont color alteration index (CAI) for this portion of the Appalachian Basin averages about 2.50. Vitrinite reflectance (R_o) values for this area are generally greater than 1.0 (the value representing optimum thermal maturity).

Figure 15: Cluster 8

Geologic Summary (Cluster 9)

Cluster 9 consists of eight counties in central and southwestern Pennsylvania, seven counties in eastern West Virginia, and one county in western Maryland. The only major gas-producing black radioactive Devonian shale in this region is the Marcellus of the Hamilton Group. The majority of this area is situated in close proximity to the central, or deepest, portion of the Appalachian Basin.

Gas production from the Devonian shale interval within the region defined by Cluster 9 may have been influenced by at least two major geologic structural features. Recurrent movement along the northeast-trending border faults associated with the basement feature (graben) known as the Rome Trough may have created some highly fractured reservoirs in the Devonian black shale. Fracturing occurring in the southern portion of Cluster 9 is most probably related to the Pine Mountain Overthrust Fault and other associated thrust faults existing in the area. In addition, the major portion of this region lies within the Appalachian Fold Belt, which contains numerous folded and faulted structures.

The overall stress ratio value for Cluster 9 is 1.0, indicating a low occurrence of natural fracturing. Drilling depths are deep, ranging from 6300 to 8500 feet, with an average depth of about 7400 feet. Aggregate radioactive shale thicknesses, which average about 80 feet, are generally not favorable for potential gas production. The conodont color alteration index (CAI) for this portion of the Appalachian Basin averages about 2.35. Vitrinite reflectance (Ro) values are generally greater than 1.0 (the value representing optimum thermal maturity).

Figure 16: Cluster 9

Geologic Summary (Cluster 10)

Cluster 10 consists of 22 counties in central and northern West Virginia and 12 counties in western Pennsylvania. The major gas-producing black radioactive Devonian shales in order of importance in this region are the Marcellus of the Hamilton Group and the Rhinestreet of the West Falls Formation. The majority of this region is situated in close proximity to the central, or deepest, portion of the Appalachian Basin.

The single most prominent geologic structure influencing Devonian shale gas production within the area of Cluster 10 is the basement feature (graben) known as the Rome Trough. Recurrent movement along the border faults associated with this feature may have created some highly fractured reservoirs within the Devonian black shale. Numerous minor folded and faulted structures also occur within this region.

The occurrence of natural fracturing within the Devonian shales in Cluster 10 appears to be low, as suggested by the mean stress ratio value of 0.99. Aggregate radioactive shale thicknesses are relatively low, ranging from 40 to 100 feet, with an average of about 80 feet. Drilling depths are deep, averaging about 6950 feet. The conodont color alteration index (CAI) for this portion of the Appalachian Basin averages about 1.75. Vitrinite reflectance (Ro) values range from about 1.0 (the value representing optimum thermal maturity) to greater than 2.0.

In order to determine the recoverable resource, data on the mean and variance of production per well, and the success ratio, are required for each cluster.

For the five clusters for which production data was available, the mean and variance of production per well were estimated from the sample data. For the other five clusters, the Delphi method was used to obtain estimates of the mean production. The Delphi method was also used to obtain estimates of the success ratio for all ten clusters.

Four participants knowledgeable in various aspects with respect to Devonian shale were each asked to rank the clusters on the basis of production per well and success ratio and also to give numerical estimates if possible. The individual rankings and the ranking obtained by averaging scores are given in Table 2, while Table 3 shows the average values of mean production per well and success ratio. Three values are given for each, corresponding to pessimistic, most likely, and optimistic estimates.

These three values were used to estimate the mean value and success ratio, on the basis that the subjective estimates followed a beta-distribution. Under this assumption, the estimates are:

$$\text{Mean} = \frac{\text{pessimistic} + 4 (\text{most likely}) + \text{optimistic}}{6}$$

and the variance (V)

$$V = \frac{(\text{optimistic} - \text{pessimistic})^2}{36}$$

The coefficients of variation for production obtained by this method were lower than those based on sample data (reflecting the tendency in subjective estimation to avoid extreme values). These values were not used; instead, the coefficient of variation was assumed to be 0.9, based on values obtained from the sample data for the other clusters.

Actual data on success ratios for exploratory Devonian shale wells were obtained from Petroleum Information Corporation and are shown in Figure 18. The success ratio based on grid-drilling would be somewhere between this figure and the figure for development wells (approximately .85 in the Cottageville and Big Sandy areas).

The production per well, and the total production from a number of

Table 2: Subjective Ranking of Devonian Shale Wells

Cluster	Participants									
	A		B		C		D		Total	
	Prod	Success Ratio	Prod	Success Ratio	Prod	Success Ratio	Prod	Success Ratio	Prod	Success Ratio
1		2.0		1.0		1.0		1.0		5.0
2		2.0		3.5		2.0		2.0		9.5
3		8.5		3.5		4.0		4.0		20.0
4		8.5		3.5		5.0		4.0		21.0
5		5.0		8.0		3.0		4.0		20.0
6	3.5	5.0	3.5	8.0	4.0	7.0	5.0	10.0	16.0	30.0
7	3.5	2.0	1.0	3.5	3.0	8.0	4.0	6.0	11.5	19.5
8	1.0	5.0	3.5	8.0	5.0	6.0	1.0	7.0	10.5	26.0
9	3.5	5.0	3.5	8.0	2.0	9.5	2.5	8.5	11.5	34.5
10	3.5	5.0	3.5	8.0	1.0	9.5	2.5	8.5	10.5	34.5

Ranking by Success Ratio	
Cluster	1
	2
	7
	3,5
	4
	8
	6
	9,10

Ranking by Production	
Cluster	8,10
	7,9
	6

(NOTE: Clusters 1 through 5 are not estimated, since actual data was available)

Table 3

Results of Delphi Method for Devonian Shale Gas Wells

Cluster	Mean Production (MMCF)			Success Ratio		
	Min	Most Likely	Max	Min	Most Likely	Max
1	2	(415)	3748	.6	.85	.9
2	56	(401)	1165	.5	.82	.9
3	31	(261)	1560	.5	.60	.7
4	46	(114)	201	.45	.55	.7
5	26	(108)	335	.5	.6	.7
6	35	100	135	.2	.37	.45
7	80	145	200	.5	.6	.7
8	85	160	210	.3	.45	.6
9	80	145	200	.1	.2	.3
10	85	160	210	.1	.2	.3
<u>Mean Values (Assuming Beta-Distribution)</u>						
Cluster	Production (MMCF)		Success Ratio			
	Mean	Standard Deviation	Mean	Standard Deviation		
1	(415)	(390)	.82	.05		
2	(401)	(266)	.78	.07		
3	(261)	(282)	.60	.03		
4	(114)	(48)	.56	.04		
5	(108)	(85)	.60	.03		
6	95	86	.36	.04		
7	143	129	.60	.03		
8	156	140	.45	.05		
9	143	129	.20	.03		
10	156	140	.20	.03		

(): Obtained from actual production data

Figure 18: Success Ratios for Exploratory Devonian Shale Wells

adjacent wells, will be affected by the well spacing. Since no actual information was available on the magnitude of this effect, a preliminary estimate was made using a radially symmetric Devonian shale reservoir simulator (13) developed within the EGSP.

The model was used to determine the 30-year production from a well, as the drainage radius (equivalent to well spacing) was varied. Four separate cases were considered, using parameters obtained by history-matching production from two wells in Mingo County, West Virginia, and two wells in Meigs County, Ohio. Graphs of cumulative 30-year production versus drainage radius are shown in Figures 19 and 20.

These results were then plotted in a normalized form by using

$$r(n) = \frac{\text{30-year cumulative production at } n\text{-acre spacing}}{\text{30-year cumulative production at 160-acre spacing}}$$

as the vertical axis, for values of n from 160 to 10 acres. The result is shown in Figure 21.

There is a large variation in these results. It was assumed here that an intermediate case would be typical of the Appalachian Basin as a whole. The recovery factors $r(n)$, and the total recoverable gas are given in Table 4.

Figure 19: 30-Year Cumulative Production Versus Spacing; Mingo County, WV, Wells No. 8944 and 9472

Figure 20: 30-Year Cumulative Production Versus Spacing; Meigs County, OH, Wells No. 9854 and 10056

Figure 21: Single Well Recovery Factors

Table 4: Effect of Spacing on Recoverable Resource

Spacing (Acres)	$r(n)$	Relative Number of Wells	Ratio of Increase in Resource	Total Recoverable Resource (TCF)
160	1.00	1	1.00	20.2
80	.84	2	1.68	34.0
40	.61	4	2.44	49.3
20	.39	8	3.10	63.0
10	.21	16	3.36	67.9

3.6 ECONOMIC AND RESOURCE MODELING

In this subsection a synopsis of the theoretical basis for obtaining the probability distribution of the economically recoverable gas is given. The following steps outline the approach.

- Step 1: In subsection 3.5, the basin was partitioned into ten different clusters, each having its own geologic and productivity characterization. The areas of the clusters range from a minimum of 1,863 square miles (Cluster 7) to a maximum area of 9,867 square miles (Cluster 10). The areas are the effective areas in terms of drillable acreage. A "grid" is superimposed on each cluster area, and each grid point represents a well. The number of wells will depend on the grid (well) spacing which, in turn, depends on reservoir properties. The effect of well spacing on productivity is seen in Figures 19, 20, and 21, cited under subsection 3.5.
- Step 2: Some of the wells, corresponding to grid-points, will be "dry holes". Success ratios for each cluster were obtained in subsection 3.5, using the Delphi method of subjective estimation. Objective estimation of productivity was considered where appropriate. The success-ratios were assumed to follow a beta-distribution where its mean and variance were calculated for each cluster, as in PERT-type calculations.
- Step 3: Following the distribution analysis performed under subsection 3.4, the lognormal distribution was adopted as a representative probability model for cumulative well productivity in each cluster. Its mathematical form is:

$$f_X(x) = \frac{1}{\sigma x \sqrt{2\pi}} \exp \frac{-(\log_e x - \mu)^2}{2\sigma^2}$$

The relative positions of the mean, median, and mode, namely, at $x = e^{\mu + \frac{\sigma^2}{2}}$, e^μ , $e^{\mu - \sigma^2}$, respectively, emphasize the positive skewness of the distribution.

- Step 4: Let $X_1, X_2, \dots, X_n, \dots$ be a sequence of independent and identically distributed random variables with mean μ_X and variance σ_X^2 . Each X_i , a random variable, corresponds to the productivity of each well as represented by every point on the grid. All wells will be assumed

to be independent of one another, in the sense that interference between wells does not exist as specified by well spacings. The wells are identically distributed, i.e., in each cluster the distribution will be lognormal with a unique mean (μ_X) and variance (σ_X^2).

Define the random variable S_N as the sum of N number of X_i s for each cluster, i.e.,

$$S_N = \sum_{i=1}^N X_i$$

S_N , represents the total recoverable gas from N wells. However, due allowance is made for the number of dry holes, and the success ratio (p) for each cluster follows a beta-distribution type where the mean and variance of p are calculated from standard PERT formulae, i.e.:

$E(p) = \mu_p = \frac{1}{6} (a + 4m + b)$, where a is the optimistic value of p, b is the pessimistic value, and m is the most likely value, and

$$V(p) = \sigma_p^2 = \frac{1}{36} (b - a)^2$$

Note that a, m, and b were estimated using a Delphi approach of subjective estimation.

In considering the success ratio, the effective number of wells is $M = pN$ where M is a random number, since p is a random variable whose mean and variance are given above, and N is the fixed number of wells corresponding to the total number of grid-points with a particular grid (well) spacing.

Using the effective number of wells M leads to:

$$S_M = \sum_{i=1}^M X_i, \text{ where } M = pN$$

Thus, S_M is a sum of a random number of random variables, whose mean (μ_S) and variance, (σ_S^2), are given by:

$$\mu_S = \mu_M \mu_X = (\mu_p N) \mu_X$$

$$\sigma_S^2 = \mu_M \cdot \sigma_X^2 + \sigma_M^2 \cdot \mu_X^2$$

$$\sigma_S^2 = (\mu_p N) \sigma_X^2 + (\sigma_p^2 N^2) \mu_X^2$$

Since M, for each cluster, is relatively large, $S_M \sim N(\mu_S, \sigma_S^2)$ by the central limit theorem (14,15). Thus, for each cluster, the total recoverable gas is normally distributed. The sum of normally distributed independent random variables is itself normally distributed. Hence, the grand total of recoverable gas (S) from all ten clusters is normally distributed with mean ($\tilde{\mu}_S$) and variance $\tilde{\sigma}_S^2$ given by:

$$\tilde{\mu}_S = \sum_{j=1}^{10} \mu_j \quad \text{where } \mu_j \text{ is the mean total}$$

recoverable gas from cluster j, and

$$\tilde{\sigma}_S^2 = \sum_{j=1}^{10} \sigma_j^2, \quad \text{where } \sigma_j^2 \text{ is the variance of total}$$

recoverable gas in cluster j.

In summary, the total recoverable gas from all ten clusters, i.e., for the whole region, is S, a random variable, where $S \sim N(\tilde{\mu}_S, \tilde{\sigma}_S^2)$.

The total recoverable gas is also the economically recoverable gas. This is established in view of well-head price trends seen in Figure 22. It is clear that price was nearly stationary up to 1973, after which prices escalated due to several causes, some of which were inflationary. In Figure 23, the major events which may have led to rising prices are shown. Currently, Devonian shale gas could sell for nearly \$4.50 per MCF, and with a cost of about 42 cents per MCF for "shooting" technology, based on 300 MMCF of production, the economic attractiveness of drilling for gas is positive. Since the price-cost differential is much higher today, with deregulation of prices and world gas prices, than in previous decades, a detailed economic analysis to establish economic viability was deemed unnecessary.

Figure 22: Nominal Average Well-Head Price Trends

Figure 23: Exogenous Factors Affecting Price Increases

Tables 5 and 6 summarize the economically recoverable gas estimates. The next section provides the major results and conclusions of this study.

Table 5: Total Recoverable Gas Estimates for Clusters and Overall Recoverable Estimates

Cluster	Area (sq. mi.)	Number (N) of Wells (160 Acres)	μ_X (MMCF per Well)	Mean Success Ratio (μ_p)	Mean Total Production μ_S -(TCF)
1	3,536	14,144	415	.82	4.8
2	3,236	12,944	401	.78	4.1
3	4,979	19,916	261	.60	3.1
4	8,853	35,412	114	.56	2.3
5	7,435	29,740	108	.60	1.9
6	4,530	18,120	95	.36	.6
7	1,863	7,452	143	.60	.6
8	2,859	11,436	156	.45	.8
9	6,545	26,180	143	.20	.8
10	9,867	39,468	156	.20	1.2
Total	53,703	214,812	$\tilde{\mu}_S = 20.2$ $\tilde{\sigma}_S^2 = 1.6$		

Table 6: Overall Recoverable Gas Estimate for the Region Based on Well Spacing

Spacing (Acres)	Total Recoverable Resource ($\bar{\mu}_s$) TCF
160	20.2
80	34.0
40	49.3
20	63.0
10	67.9

4.0 FINAL RESULTS AND CONCLUSIONS

A summary of the final results and conclusions is presented below. With the approach and method of analysis adopted in this study, the economically recoverable gas estimates are estimated in terms of a probability distribution. This implies that the inherent uncertainty associated with such interval estimates is quantified by means of probabilities.

- (i) The distribution of the economically recoverable gas is a Normal distribution having an expected total gas recoverable value ($\tilde{\mu}_g$) of 20.2 TCF with a standard deviation ($\tilde{\sigma}_g$) of 1.6 TCF for the Appalachian Basin. The estimate is conditional on "shooting" technology being used on 160-acre well spacing. From properties of the Normal distribution, it is seen that a 95 percent probability exists for the recoverable gas resource to lie between 17.06 TCF and 23.34 TCF. The Normal distribution curve with this interval estimate is shown in Figure 24. In terms of barrels of oil equivalent, 20.2 TCF is nearly equivalent to 3.5 billion barrels of oil, which at a cost of \$30 per barrel (Saudi crude) amounts to a potential cost saving in imported oil of nearly 104 billion dollars at current prices. In Table 7, the shale gas impact on oil import substitution is given.
- (ii) It is observed that the estimates are sensitive to well spacing, as seen in Table 8, wherein the estimates generated in this study are compared to estimates of certain similar studies. Also, the basin was partitioned into ten clusters (Figure 7, cited in subsection 3.5) based on production and geologic attributes. The relative productivity of these clusters is shown in Table 5, cited in subsection 3.6.
- (iii) The lognormal distribution is a remarkably good probability model to characterize the distribution of well productivity. This is true in relatively small areas, such as counties, and in larger regional areas. Its interpretation from an exploration point of view can be quite significant. It is noted that even in relatively productive but small

Figure 24: Distribution of the Economically Recoverable Resource

Table 7: Shale Gas Impact on Oil Import Substitution

Well Spacing (acres)	SAI Recoverable Gas Estimates (TCF)	Equivalent Oil Barrels* (billions)	Equivalent Oil Cost-Savings** (\$billions)
160	20.2	3.47	104.23
80	34.0	5.84	175.44
40	49.3	8.48	254.39
20	63.0	10.83	325.08
<p>* Conversion: 1 TCF = 172 million barrels of oil.</p> <p>** Substitution cost saving based on 1 barrel of Saudi crude priced at \$30 (1980).</p>			

Table 8: Comparison of Recoverable Gas Estimates for Devonian Shale

Source	Area (square miles)	Well Spacing (acres)	Production Span (years)	Shot Wells	Fractured Wells
National Petroleum Council (NPC)	62,000	160	30	25.3	37.4
Lewin & Associates	56,000	150	30	--	*10.5 (Base) *18.6-25.3 (Advanced)
Office of Technology Assessment (OTA)	16,300	150	30	11-20**	15-25**
Science Applications, Inc. (SAI)	53,703	160 80 40 20	10-30 10-30 10-30 10-30	20.2 34.0 49.3 63.0	--
<p>* Base and Advanced cases differ in area considered, success ratios, and production per well.</p> <p>** Based on \$3.00/MCF.</p>					

areas of the basin, such as Floyd and Jackson Counties, intense exploration might be required to find the higher productivity wells having smaller probabilities of occurrence, as represented in the tail of the lognormal distribution. This situation is even more pronounced in areas with low average production potential, where drilling a large number of wells may not produce more gas than average. Drilling large numbers of wells without detailed exploration in the shales can, by the statistical law of large numbers, produce this net effect of low average recovery. The average recovery is low because of the large probability density of low productivity wells as seen by the relative positions of the median and mean of the lognormal distribution.

The lognormal distribution could also serve as a probability model of fracture density or reservoir capacity if well productivity is directly related to fracture density. However, the implication of such a relationship, if it exists, is of no immediate practical use other than the need, mentioned earlier, for finding those spots of high fracture density which have relatively low frequencies of occurrence in the shales, as indicated by low tail probabilities of the lognormal distribution.

(iv) The most likely, expected value of 20.2 TCF that could be obtained with shooting technology on 160-acre well spacing is sufficient to meet regional demand for about ten years. Annual gas demand combined for the states of New Jersey, New York, Pennsylvania, Ohio, Virginia, West Virginia, and Kentucky is about 2 TCF for the past few years, with national demand at 19-20 TCF. The marketing of shale gas is already enhanced by existing infrastructure, such as pipeline networks, and the proximity to industrial and population centers in Ohio, Pennsylvania, and in some northeastern states.

(v) The production schedule for the marketing of shale gas in the future will depend, among other factors, on how producers with market power react to economic conditions. Economic resource theory (16, 17) states that producers with market power will tend to hold gas in the ground if their expectations are for higher prices well above their discount rates. Cutting supply and, thereby, putting even more pressure on prices has meant that holding gas in the ground is a good investment for a higher-price future. The demand for gas has been somewhat price-inelastic in the short-to-medium term, and increased price, after partial deregulation, has led to increased revenues.

That increased drilling has occurred with increasing prices is evident in Appalachia and elsewhere, and may even contribute to a temporary local or regional surplus of gas. Hefty gas price increases could alone alter the usually-regarded marginal status of low-productivity Devonian shale gas wells to good economic investments. As a result, some operators in quick pursuit of quick monetary returns may tend to overlook new and emerging technology gains, and settle for well-established and known means of stimulation technology, such as shooting.

(vi) For "self-help" customers, such as schools and colleges, hospitals and religious institutions, and small industry, which require considerably less energy for heating and basic power needs, the Devonian shale gas well is an attractive alternative to rising energy costs and possible future curtailments of energy supply. The shale well has typically a long (greater than 30 years) production lifespan. Such a long lifespan makes it a dependable and stable source of energy for those self-help customers who cannot afford steadily rising prices, which may cause severe hardship for some, or diminishing profit margins for others.

(vii) Significant improvements in gas recovery can be obtained by hydraulic fracturing. In one study, Ray (2) showed that waterfrac-treated wells perform better than shot wells in terms of percentage production increases. These percentage increases can be nearly as high as 100 percent in some cases. However, these improvements seem to cover only those cases where low open flows (<300 MCFD) are considered. In Figure 25, the cumulative production, as a percentage incremental change of waterfrac over shot wells, for the first four years is shown. It is readily seen that a "law of diminishing returns" applies as the range of open flows exceeds the 300 MCFD boundary. This implies that stimulation technology may not be a factor in significantly improving those wells with open flows greater than 300 MCFD. In Figure 26, a comparison of foam frac over shot treatment is shown. Once again, a significant improvement in gas recovery is noticed. Over a 30-year period, for the specific case cited, an increase in cumulative production from 270 MMCF to 470 MMCF is projected if foam frac were used instead of shooting. This is nearly a 75 percent increase. Such improvements, if sustained, for the large number of wells with low open flows, could significantly increase ultimate gas recovery. Based on initial results a rough projection of about 10 TCF addition to the

Figure 25: Cumulative Incremental Production Percentage
Comparison of Hydraulically Fractured Wells
Over Shot Wells for Open Flow Range

Figure 26: Cumulative Production of Shale Wells, Frac Versus Shot
(C. A. Komar, Personal Communication)

normally expected recoverable gas from the shales seems reasonable. More detailed analysis to include the relative benefits and costs of new technology, such as foam fracturing, and emerging technology, such as tailored-pulse-loading, is required as more data becomes available. Preliminary indications suggest that foam fracturing is more cost-effective than shooting.

REFERENCES

1. Komar, C. A., Yost, A. B., Sinclair, A. R., Foam Fracturing the Devonian Shale, World Oil, July (1980).
2. Ray, E. O., Devonian Shale Production, Eastern Kentucky Field, UNITAR Conference, Pergammon Press, NY (1976).
3. U.S. DOE/METC, Special Publication on Unconventional Gas from Shales (Revised Edition), January (1980).
4. Pulle, C. V., A Hydrodynamic Analogy of Production Decline in Devonian Shale Wells, Unpublished Technical Paper, April (1980).
5. Cremer, B., Alternative Gas Workshop Proceedings, Los Alamos Laboratory, March (1980).
6. McKetta, S. F., Earth Stress Relationships in the Appalachian Basin, SPE/DOE 8955, Unconventional Gas Recovery Symposium, Pittsburgh, PA (1980).
7. Streib, D. L., Eastern Gas Shales Project Outgassing Analysis Special Report, METC/CR-80/2 (1980).
8. National Petroleum Council (NPC), Unconventional Gas Sources, Draft Report, September (1979).
9. Office of Technology Assessment (OTA), Congress of the United States, Status Report on the Gas Potential from Devonian Shales of the Appalachian Basin, November (1977).
10. USGS, Oil and Gas Data from Paleozoic Rocks in the Appalachian Basin; Maps for assessing hydrocarbon potential and thermal maturity; Map No. 1-917-E (1978).
11. Johnson, S. C., Hierarchical Clustering Schemes, Psychometrika, Vol. 32, p. 241 (1967).
12. Gess, G., and Bois, C., Study of Petroleum Zones: A Contribution to the Appraisal of Hydrocarbon Resources, UNITAR Conference, Pergammon Press, NY (1976).
13. Science Applications, Inc., Modeling of Devonian Shale Gas Reservoirs, Final Report, September (1979).
14. Kendall, M. G., Stuart, A., The Advanced Theory of Statistics, 2 Vols., Griffin & Co., London (1961).
15. Lindley, D. V., Probability and Statistics from a Bayesian Viewpoint, 2 Vols., Cambridge University Press (1965).
16. Dasgupta, P. S., Heal, G. M., Economic Theory and Exhaustible Resources, Cambridge University Press (1979).
17. Solow, R. M., The Economics of Resources and the Resources of Economics, American Economic Review, May (1974).

APPENDIX A

Cluster	State	County	Remaining Drillable Area (sq. mi.)	Radioactive Shale Thickness (Feet)	CAI	Drilling Depth (Feet)	Stress Ratio
1	KY	Bell	237		1.50	3500	0.43
		Boyd	146		1.75	2300	0.73
		Floyd	13		1.75	3000	0.52
		Harlan	300		1.75	4500	0.46
		Johnson	150		1.75	2100	0.80
		Knott	36		1.75	3500	0.43
		Lawrence	255		1.75	2300	0.73
		Leslie	257		1.75	3400	0.44
		Letcher	171		1.75	4200	0.43
		Magoffin	180		1.75	1900	0.85
		Martin	71		1.75	3000	0.52
		Perry	134		1.75	3900	0.43
		Pike	275		1.75	4000	0.43
	WV	Cabell	31		1.75	4000	0.43
		Jackson	309		1.75	4800	0.51
		Lincoln	50		1.75	4400	0.45
		Logan	228		2.25	5200	0.60
		Mason	291		1.75	4200	0.43
		Mingo	158		1.75	5000	0.55
		Putnam	143		1.75	4700	0.49
		Wayne	101		1.75	3500	0.43
MEAN: (Total)			3536	332	1.76	3686	.53
2	VA	Buchanan	346		2.25	5600	0.75
		Dickenson	219		1.75	5200	0.60
		Lee	145		2.25	4600	0.47
		Russell	32		2.25	5700	0.80
		Tazewell	107		2.00	5800	0.85
		Wise	249		2.25	5200	0.60
	WV	Boone	277		1.75	5700	0.80
		Kanawha	514		1.75	5300	0.64
		McDowell	331		2.25	6600	1.00
		Roane	324		1.75	6200	1.00
		Wirt	159		1.75	5500	0.70
		Wood	230		1.75	5400	0.68
		Wyoming	303		2.25	7000	1.00
		MEAN: (Total)			3236	233	2.00

Figure 27: Division of Appalachian Basin Into Ten Clusters

Cluster	State	County	Remaining Drillable Area (sq. mi.)	Radioactive Shale Thickness (Feet)	CAI	Drilling Depth (Feet)	Stress Ratio
3	KY	Breathitt	316		1.00	2500	0.66
	NY	Cattaraugus	810		1.00	2700	0.60
	OH	Athens	262		1.00	3100	0.50
		Coshocton	283		1.00	2600	0.63
		Gallia	245		1.00	3000	0.52
		Guernsey	249		1.00	4300	0.43
		Holmes	213		1.00	2400	0.60
		Lawrence	217		1.00	2800	0.57
		Morgan	285		1.00	3700	0.43
		Muskingum	334		1.00	3000	0.52
		Perry	213		1.00	2500	0.66
		Portage	245		1.00	2500	0.66
		Stark	259		1.00	2700	0.60
		Tuscarawas	286		1.00	3300	0.47
	WV	Hardy	328		1.00	4500	0.46
		Morgan	45		1.00	4000	0.43
		Pendleton	389		1.00	5500	0.70
MEAN: (Total) 4979				146	1.0	3240	0.56

Cluster	State	County	Remaining Drillable Area (sq. mi.)	Radioactive Shale Thickness (Feet)	CAI	Drilling Depth (Feet)	Stress Ratio
4	KY	Clay	474		1.75	2200	0.77
		Knox	239		1.75	2000	0.86
		Owsley	126		1.00	2300	0.73
	MD	Allegany	283		1.50	5500	0.70
	NY	Allegany	701		1.75	3500	0.43
		Steuben	899		2.00	3500	0.43
	OH	Belmont	261		1.75	5000	0.56
		Carroll	202		1.75	3900	0.43
		Columbiana	272		1.75	4100	0.43
		Harrison	197		1.75	4200	0.43
		Jefferson	212		1.75	4300	0.45
		Mahoning	205		1.75	3500	0.43
		Meigs	216		1.75	3300	0.47
		Monroe	222		1.75	5500	0.70
		Noble	206		1.75	4500	0.46
		Trumbull	272		1.75	2800	0.57
		Washington	331		1.75	5200	0.60
	PA	Beaver	181		1.75	5000	0.55
		Crawford	543		1.75	3000	0.52
		Forest	250		1.75	5000	0.55
		Lawrence	175		1.75	4200	0.43
		McKean	610		1.75	5000	0.55
		Mercer	292		1.75	3800	0.43
		Venango	390		1.75	4500	0.46
		Warren	544		1.75	4000	0.43
	TN	Claiborne	50		1.50	3200	0.48
	WV	Brooke	49		1.75	4800	0.51
		Hampshire	358		1.75	4500	0.46
		Hancock	39		1.75	4700	0.49
		Ohio	54		1.75	5500	0.70
MEAN: (Total)			8853	103	1.72	4083	0.53

Cluster	State	County	Remaining Drillable Area (sq. mi.)	Radioactive Shale Thickness (Feet)	CAI	Drilling Depth (Feet)	Stress Ratio
5	KY	Carter	397		1.00	1400	1.00
		Elliot	240		1.00	1500	1.00
		Greenup	351		1.00	1500	1.00
		Morgan	236		1.00	1700	1.00
		Wolfe	145		1.00	1300	1.00
	NY	Chautauqua	710		1.00	2000	0.86
	OH	Ashland	201		1.00	1500	1.00
		Ashtabula	317		1.00	2000	0.86
		Crawford	149		1.00	500	1.00
		Cuyahoga	28		1.00	1400	1.00
		Delaware	115		1.00	750	1.00
		Erie	48		1.00	500	1.00
		Fairfield	259		1.00	1500	1.00
		Franklin	82		1.00	800	1.00
		Geauga	187		1.00	2000	0.86
		Hocking	209		1.00	2100	0.80
		Huron	219		1.00	500	1.00
		Jackson	219		1.00	2000	0.86
		Knox	269		1.00	1500	1.00
		Lake	104		1.00	1700	1.00
		Licking	353		1.00	1800	0.95
		Lorain	221		1.00	1200	1.00
		Medina	213		1.00	1800	0.95
		Morrow	203		1.75	750	1.00
		Pickaway	96		1.00	900	1.00
		Pike	141		1.00	900	1.00
		Richland	258		1.00	1200	1.00
		Ross	183		1.00	1200	1.00
		Scioto	316		1.00	1100	1.00
		Summitt	128		1.00	2100	0.80
		Vinton	210		1.00	2100	0.80
		Wayne	272		1.00	2000	0.86
	PA	Erie	356		1.50	2300	0.73
MEAN: (Total)			7454	185	1.04	1583	.94

Cluster	State	County	Remaining Drillable Area (sq. mi.)	Radioactive Shale Thickness (Feet)	CAI	Drilling Depth (Feet)	Stress Ratio
6	KY	Casey	278		1.00	500	1.00
		Clinton	122		1.50	1000	1.00
		Jackson	216		1.00	750	1.00
		Laurel	285		1.00	750	1.00
		Lee	134		1.00	1400	1.00
		Lincoln	218		1.00	500	1.00
		McCreary	268		1.75	900	1.00
		Menifee	134		1.00	1000	1.00
		Powell	111		1.00	1000	1.00
		Pulaski	418		1.00	750	1.00
		Rockcastle	199		1.00	750	1.00
		Russell	152		1.50	500	1.00
		Wayne	440		1.75	500	1.00
		Whitley	294		1.50	1300	1.00
		TN	Campbell	189		1.25	1500
	Fentress		279		1.75	1000	1.00
	Morgan		151		1.75	1500	1.00
	Overton		247		1.25	1000	1.00
	Pickett		89		1.75	800	1.00
	Scott	305		1.75	1200	1.00	
MEAN				58	1.33	930	1.00
7	NY	Erie	524		2.25	1000	1.00
		Livingston	381		2.25	1500	1.00
		Ontario	358		2.50	1200	1.00
		Wyoming	380		2.25	2000	0.86
		Yates	220		2.25	1500	1.00
MEAN:				41	2.30	1440	0.97
8	NY	Chemung	272		2.25	5000	0.55
		Schuyler	207		2.25	3100	0.50
		Tioga	348		2.50	4800	0.51
		Tompkins	312		2.50	2800	0.57
	PA	Bradford	636		2.75	5500	0.70
		Tioga	631		2.25	5500	0.70
	WV	Grant	268		2.75	5000	0.55
		Mineral	185		2.75	5500	0.70
		MEAN: (Total) 9251				71	2.50

Cluster	State	County	Remaining Drillable Area (Sq. mi.)	Radioactive Shale Thickness (Feet)	CAI	Drilling Depth (Feet)	Stress Ratio
9	MD	Garrett	428		2.00	7300	1.00
		PA					
	PA	Cambria	349		2.25	8000	1.00
		Centre	316		2.25	8000	1.00
		Clearfield	657		2.00	7500	1.00
		Clinton	330		2.25	7500	1.00
		Fayette	387		2.00	8300	1.00
		Lycoming	420		2.25	7000	1.00
		Somerset	574		2.50	8500	1.00
		Sullivan	272		3.25	7000	1.00
	WV	Greenbrier	690		2.00	7000	1.00
		Mercer	204		2.75	7000	1.00
		Monroe	151		2.75	7000	1.00
		Pocahontas	577		2.00	7500	1.00
		Randolph	699		2.00	7000	1.00
		Summers	212		3.25	7000	1.00
		Tucker	279		2.25	6300	1.00
MEAN: (Total)			6545	82	2.36	7369	1.00

Cluster	State	County	Remaining Drillable Area (Sq. mi.)	Radioactive Shale Thickness (Feet)	CAI	Drilling Depth (Feet)	Stress Ratio
10	PA	Allegheny	95		1.75	6500	1.00
		Armstrong	320		1.75	6700	1.00
		Butler	387		1.75	5200	.06
		Cameron	218		1.75	6000	1.00
		Clarion	333		1.75	5800	.85
		Elk	461		1.75	6300	1.00
		Greene	210		1.75	7600	1.00
		Indiana	420		1.75	7500	1.00
		Jefferson	343		1.75	6500	1.00
		Potter	609		1.75	6000	1.00
		Washington	423		1.75	6800	1.00
		Westmoreland	393		1.75	7200	1.00
	WV	Barbour	226		1.75	7500	1.00
		Braxton	343		1.75	7200	1.00
		Calhoun	189		1.75	6300	1.00
		Clay	225		1.75	6400	1.00
		Doddridge	217		1.75	6800	1.00
		Fayette	408		1.75	7000	1.00
		Gilmer	220		1.75	7000	1.00
		Harrison	215		1.75	7500	1.00
		Lewis	240		1.75	7500	1.00
		Marion	194		1.75	7900	1.00
		Marshall	197		1.75	6400	1.00
		Monongalia	231		1.75	7900	1.00
		Nicholas	421		1.75	7000	1.00
		Pleasants	85		1.75	6000	0.98
		Preston	419		1.75	7500	1.00
		Raleigh	384		1.75	7000	1.00
		Ritchie	292		1.75	6200	1.00
		Taylor	133		1.75	7900	1.00
		Tyler	172		1.75	6500	1.00
		Upshur	236		1.75	8000	1.00
		Webster	370		1.75	7900	1.00
		Wetzel	238		1.75	6800	1.00
MEAN: (Total)			9867	77.4	1.75	6942	.99

Figure 28: Histogram for Kentucky

Figure 29: Histogram for Floyd County, KY

Figure 30: Histogram for Knott County, KY

Figure 31: Histogram for Martin County, KY

Figure 32: Histogram for Ohio

Figure 33: Histogram for Lawrence County, OH

FREQUENCY

LICKING, OH: PRODUCTIVITY CHARACTERISTICS

MRST : 330'

CAI : 1.0

DEPTH : 1500'

MIN : 26 MMCF

MAX : 335 MMCF

MEAN : 108 MMCF

N : 19

STRESS RATIO = 0.7 → 1.0

Figure 34: Histogram for Licking County, OH

Figure 36: Histogram for West Virginia

Figure 37: Histogram for Boone County, WV

FREQUENCY

CABELL WV PRODUCTIVITY CHARACTERISTICS

MRST : 347'
CAI : 1.75
DEPTH : 4000'

MIN : 2 MMCF
MAX : 1069 MMCF
MEAN : 408 MMCF
N : 20
STRESS RATIO = 0.5

Figure 38: Histogram for Cabell County, WV

Figure 39: Histogram for Jackson County, WV

Figure 40: Histogram for Kanawha County, WV

Figure 41: Histogram for Lincoln County, WV

Figure 42: Histogram for Logan County, WV

Figure 43: Histogram for Mingo County, WV

Figure 44: Histogram for Wayne County, WV

Figure 45: Probability Plot (Mingo, WV)

Figure 46: Probability Plot (Logan, WV)

Figure 47: Probability Plot (Lincoln, WV)

Figure 48: Probability Plot (Jackson, WV)

Figure 49: Probability Plot (Martin, KY)

Figure 50: Probability Plot (WV)

Figure 51: Probability Plot (KY)

Figure 52: Probability Plot (OH)