of

**GEOHYDROLOGIC FEASIBILITY STUDY OF THE NORTHERN AND CENTRAL
APPALACHIAN BASIN AREAS FOR THE POTENTIAL APPLICATION OF A
PRODUCTION PROCESS PATENTED BY JACK W. MCINTYRE**

By
David Kvasnicka

March 1994

Work Performed Under Jack McIntyre/DOE Contract No. DE-FG46-92-R699202

For
Jack W. McIntyre
Fort Stockton, Texas

And

U.S. Department of Energy
Office of Scientific and Technical Information (OSTI)
Oak Ridge, Tennessee

DISCLAIMER

By
Geraghty & Miller, Inc.
Midland, Texas

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, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

GERAGHTY & MILLER, INC.

CONTENTS

ABSTRACT	1
INTRODUCTION	2
PHYSIOGRAPHIC SETTING	2
CENTRAL APPALACHIAN BASIN	2
NORTHERN APPALACHIAN BASIN	4
GEOLOGIC SETTING	4
CENTRAL APPALACHIAN BASIN	4
NORTHERN APPALACHIAN BASIN	7
CENTRAL APPALACHIAN BASIN	8
CENTRAL BASIN STRATIGRAPHY	8
Scope of Discussion	8
Mississippian and Pennsylvanian Stratigraphy	8
Overview of Mississippian Stratigraphy	10
Mauch Chunk Group	10
Bluefield Formation	11
Hinton Formation	11
Bluestone Formation	11
Mauch Chunk Formation	11
Pennsylvanian Stratigraphy	13
Pottsville Group	13
Pocahontas Formation	14
Coal Stratigraphy	14
Lee Formation (Southwestern Virginia)	15
Coal Stratigraphy	15
Norton Formation (Southwestern Virginia)	15
Coal Stratigraphy	15
New River Formation (West Virginia and Virginia)	16
Coal Stratigraphy	16
Kanawha Formation	17
Coal Stratigraphy	17
Primary Methane Target Area	17
Coalbed Reservoir Parameters	18
Additional Published Studies	20
Coalbed Cleat Development and Orientation	20
Groundwater Aquifer Distribution	23
Mississippian Strata	23
Pennsylvanian Strata	23
Conclusions-Central Appalachian Basin	23

CONTENTS (cont'd)

NORTHERN APPALACHIAN BASIN	24
NORTHERN BASIN STRATIGRAPHY	24
Pennsylvanian Strata and the Dunkard Group	24
Pottsville Group	26
Allegheny Formation	26
Conemaugh Group	27
Monongahela Group	27
Dunkard Group	28
Principal Coal-Bearing Formations	28
Pottsville Group	28
Allegheny Group	29
Conemaugh Group	31
Monongahela Group	31
Dunkard Group	32
PRIMARY METHANE TARGET AREAS	32
Coalbed Cleat Development and Orientation	35
Groundwater Aquifer Distribution	35
Conclusions-Northern Appalachian Basin	35
REFERENCES	37

GEOHYDROLOGIC FEASIBILITY STUDY OF THE NORTHERN AND CENTRAL APPALACHIAN BASIN AREAS FOR THE POTENTIAL APPLICATION OF A PRODUCTION PROCESS PATENTED BY JACK W. MCINTYRE

ABSTRACT

Geraghty & Miller, Inc. of Midland, Texas conducted geologic and hydrologic feasibility studies of the potential applicability of a patented (U.S. Patent Office # 4,766,957) process developed by Jack W. McIntyre for the recovery of natural gas from coalbed/sand formations in the Northern and Central Appalachian basin areas. General research, based on a review of published literature from both public and private sources, indicates that the generally thin, but numerous coalbeds found in the greater Appalachian Basin area do exhibit some potential for the application of this patented process.

Estimates of total gas reserves in-place (Gas Research Institute, July 1991) for coalbeds in the Central and Northern Appalachian Basin areas are 5 trillion cubic feet (TCF) and 61 TCF respectively.

Produced waters associated with coal deposits in the greater Appalachian Basin area can be characterized on the basis of established but limited production of coalbed methane. Central Appalachian coals generally produce small quantities of water (less than 50 barrels of water per day for the average producing well) which is high in total dissolved solids (TDS), greater than 30,000 parts per million (ppm). The chemical quality of water produced from these coal seams represents a significant disposal challenge to the operators of methane-producing wells in the Central Appalachian Basin.

By contrast, water associated with the production of coalbed methane in the Northern Appalachian Basin is generally fair to good quality, and daily production volumes are low. However, the relatively slow desorption of methane gas from Northern Appalachian coals may result in a greater net volume of produced water over the economic life of the well. The well operator must respond to long-term disposal needs.

INTRODUCTION

The greater Appalachian basin area is comprised of two related but distinct geologic features, referred to as the Central and Northern Basins. Each of these basins covers more than one physiographic province, and each underlies portions of several different states. For the purpose of this document, these two basin areas are addressed in separate discussions, each adhering to a singular format.

PHYSIOGRAPHIC SETTING

CENTRAL APPALACHIAN BASIN

The Central Appalachian Basin underlies portions of West Virginia, Virginia, Kentucky, Tennessee and Maryland and covers a total area of approximately 22,850 square miles (Figure 1). The Central Basin is found within two physiographic provinces, the Appalachian Plateau (central and northern West Virginia) and the Valley and Ridge Province (eastern West Virginia and extreme southwestern Virginia).

The Appalachian Plateau is a nearly horizontal to gently dipping area with surface elevations along the eastern perimeter ranging from 1,000 to 3,000 feet above the adjacent Valley and Ridge Province. Surface elevations generally decrease to the west of the high eastern ridge referred to as the Allegheny Front.

The Valley and Ridge Province consists of narrow, elongated series of mountain ridges and adjoining valleys. These features have a strong northeast-southwest orientation and were formed as the result of well-documented structural deformation of the region (briefly discussed later in this document).

Figure 1. Location of the Central Appalachian Basin (after GRI, March 1990).

NORTHERN APPALACHIAN BASIN

The Northern Appalachian Basin is located within portions of the following states: Pennsylvania, Maryland, West Virginia, Ohio and Kentucky; having an areal extent of 43,000 square miles (Figure 2). The Northern basin area is found within the Allegheny Plateau physiographic province. Surface elevations generally decrease to the west into Ohio and little variation is observed throughout the remainder of the basin area. Surface drainage is also to the west.

GEOLOGIC SETTING

CENTRAL APPALACHIAN BASIN

The Central Appalachian Basin is a narrow, northeast/southwest trending feature that covers an area of approximately 23,000 square miles in portions of Tennessee, Kentucky, Virginia, and West Virginia (Figure 1). The northeast and southwest boundaries of the basin are defined by surface exposures of Pennsylvanian-age sedimentary rocks. On the southeast, thrust faulting associated with the Pine Mountain Overthrust block truncates these strata. The northwestern basin boundary is defined as the outcrop of Alleghenian-age sedimentary rocks of the Northern Appalachian Basin. The outcrop line of the Alleghenian strata follows the trace of the Rome Trough, a major structural feature in the area (Hunt et al 1991). Structural features associated with the Central Appalachian Basin are depicted in Figure 3.

The structural character of the Central Basin is closely aligned with the surface physiography described above. The Appalachian Plateau overlies many broad anticlines and synclines which are largely parallel to the northeast-southwest orientation of the basin axis.

The Valley and Ridge Province is underlain by more complex and more numerous anticlines, synclines and overthrust faults. Moderate to very steep structural dips are very

Figure 2. Location of the Northern Appalachian Basin (after GRI, March 1990).

Figure 3. Structural Features within the Central Appalachian Basin (after Adams, 1982).

common and overturned stratigraphy is also known to occur in some areas.

The structural development of the Central Basin is largely the result of compressional deformation associated with the growth of the Appalachian Mountains, which occurred late in the Paleozoic era during Mississippian and Pennsylvanian time. Some faulting in the present basin area considerably predates the Late Paleozoic and is known to have occurred from Lower Cambrian to Devonian time. The Rome Trough is a graben structure which originated during the Late Cambrian and remained active throughout the balance of Paleozoic time. This feature influenced patterns of deposition across the northwest portion of the Central Basin and defines the structural boundary between the Central and Northern Appalachian basins.

NORTHERN APPALACHIAN BASIN

The Northern Appalachian Basin is a northeast-southeast trending feature of Pennsylvanian age which encompasses and includes the younger, Permian age Dunkard Basin. The Kanawha Section of the Plateau is gently folded and exhibits dips of approximately 30 feet per mile. In contrast, the sharp, asymmetric, north-south trending Burning Springs Anticline exhibits dips of 15 to 20 degrees in the Allegheny Mountain Section. The folds have undergone extensive erosion which has resulted in a rugged mountainous appearance (Adams et al 1984).

At the beginning of the Pennsylvanian Period, some structure was present which assisted in controlling the deposition of strata during the Pennsylvanian and Dunkard time. It appears that at least part of the gently folding plateau covers a more intensely folded and faulted strata or a less intensely folded strata (Adams et al 1984).

Outcrops of Pennsylvanian age bounds the west, north and northeast sides of the basin. The basin is bounded on the south and southeast by the Rome Trough hinge line. The Rome Trough is a graben structure which formed during the early Cambrian. The

trough affected sedimentation patterns in the Devonian, Mississippian, and Pennsylvanian (Adams et al 1984).

CENTRAL APPALACHIAN BASIN

CENTRAL BASIN STRATIGRAPHY

Scope of Discussion

The Central Basin contains sediments ranging in age from Pre-Cambrian to Lower Permian. Due to the lateral extent of the basin, across the boundaries of five states, the stratigraphic nomenclature applied to these sediments is quite complex and regarded by the author as beyond the scope of this discussion. In recognition of this limitation, further review of the stratigraphy of the Central Basin will address only the Mississippian and Pennsylvanian age formations (Figure 4). The review will center on southeastern West Virginia and southwestern Virginia. This area overlies the deepest portion of the Central Basin and is the center of coal production. The highest estimated gas-in-place resources are concentrated within a small area near the center of the basin.

Mississippian and Pennsylvanian Stratigraphy

The depositional environment in the present Central Appalachian Basin can be characterized by regressive and transgressive marine margins across a shallow basin undergoing steady but slow subsidence. Deposition of sediments was nearly continuous during the Mississippian and Pennsylvanian periods.

The maximum combined interval thickness of these sediments is observed along the main axis of the basin, along the southeast margin of the basin (southeastern West Virginia and southwestern Virginia). In southwestern Virginia, the combined Mississippian and Pennsylvanian section is nearly 17,000 feet thick. The interval thins relatively rapidly to the

Conemaugh Group	
Charleston Sandstone Group 107 m (350 ft maximum)	No. 6 Block coal Upper No. 5 Block coal (North Coalburg) Lower No. 5 Block coal (No. 5 Block) Homewood Sandstone Kanawha Black flint ¹ Stockton coal
Kanawha Formation 640 m (2100 ft maximum)	Coalburg coal Winifrede coal Chilton "A" coal Winifrede limestone ¹ Chilton coal Hemshaw coal Dingess coal Dingess limestone ¹ Seth limestone ¹ Cedar Grove coal Alma coal Campbells Creek limestone ¹ Peerless coal Campbells Creek coal Powellton coal Stockton limestone ¹ Unnamed shale ² Eagle coal Eagle limestone ¹ Lower War Eagle coal Gilbert shale ¹ Gilbert coal Douglas coal Douglas sandstone Douglas shale ²
New River Formation 0 to 314 m (1030 ft)	Nuttall sandstone Skelt shale ² Hartridge shale ² Sewell coal ("Pocahontas No. 12") Beckley coal ("Pocahontas No. 11") Quinnimont shale Fire Creek coal ("Pocahontas No. 10") Pocahontas No. 9 coal Pineville sandstone Pocahontas No. 8 coal
Pocahontas Formation 0 to 216 m (710 ft)	Flattop Mountain sandstone Pocahontas No. 6 coal Pocahontas No. 4 coal Unnamed shale ¹ Pocahontas No. 3 coal North Fork shale ² Squire Jim coal
MISSISSIPPIAN SYSTEM	

¹Marine²Fresh or brackish

Figure 4. Pennsylvanian Stratigraphy Central Appalachian Basin (Southern West Virginia) (after Arkle et al, 1979).

west. Nearby, in Wyoming and McDowell Counties, West Virginia the gross interval thickness is approximately 6,200 feet.

The Mississippian section consists of marine shales, carbonaceous (marine margin) shales, fluvial sands and coals. The principal formation unit in the Upper Mississippian is the Mauch Chunk Group. The Mauch Chunk is approximately 2,300 feet thick near the basin axis and thins to less than 300 feet in central West Virginia and to less than 10 feet in the western portion of the state. This thinning is due to an erosional unconformity and increased distance from the primary sediment source area (to the southeast).

Overview of Mississippian Stratigraphy

The Mauch Chunk Group represents the deposition of large volumes of detritus generated during the uplift of the Appalachian landmass to the east and southeast of the present Central Basin area. In the southern end of the Basin, in relative proximity to the primary source of sediment during Lower Mississippian time, the Mauch Chunk is underlain by significant thicknesses of older Greenbrier Limestone, Maccrady Formation (red shale), and Pocono Formation (basal Mississippian unit - a sandstone). Figure 4 depicts the underlying "Catskill Island", consisting of the Devonian Hampshire Formation (red bed shales). This feature has been interpreted by Dally (1956) as representing a deltaic lobe which stood above sea level. The crest of this lobe is referred to, in Dally's thesis, as a depositional "hinge line." To the south of this hinge line, the Hampshire Formation is overlain by the Chemung Group (Upper Devonian sandstone) in a basinal depositional environment flanking the aforementioned "Catskill Island."

Mauch Chunk Group

The Mauch Chunk Group in southern West Virginia is nearly 3,300 feet thick (Arkle et al, 1979) and consists of four distinct formations. These units are (in ascending order): 1. Bluefield Formation, the Hinton Formation, the Bluestone Formation and the Mauch Chunk Formation.

Bluefield Formation

The Bluefield Formation consists primarily of interbedded gray and green marine shales and limestones with some occurrence of terrestrial shale and sandstone. Some minor coals are associated with terrestrial deposition.

Hinton Formation

The Hinton Formation is composed of interbedded red, arenaceous, partly calcareous shale and siltstone; ferruginous and calcareous sandstone; numerous fossiliferous limestone units; and some coal with associated underclay.

Bluestone Formation

The Bluestone Formation consists of red and green calcareous shale and siltstone, variegated sandstone, shale and lenticular limestone, and coal and associated underclay. Arkle et al (1979) states that paleontological evidence suggests a coastal plain depositional environment.

Mauch Chunk Formation

To the north of the "Catskill Island" hinge line, the Mauch Chunk Group thins dramatically (Figure 5) and the three older Mississippian units lose their identity. Arkle et al (1979) states that "such drastic thinning is due to (1) the erosional unconformity at the top of the Mississippian System and (2) the increased distance from the southeastern source of Mississippian clastic materials (Dennison and Wheeler, 1975)".

The Mauch Chunk Formation is lithologically persistent and, as in the south, consists primarily of undifferentiated red and green shale interbedded with green sandstone. Some coal is found in the southern depositional area but is lacking in the north (Arkle, 1979).

Figure 5. Cross Section of Mississippian Strata along Outcrop Belt (after Arkle et al, 1979).

Pennsylvanian Stratigraphy

The Pennsylvanian section in northeast West Virginia consists of the following formations (listed in ascending order: Pottsville, Allegheny, and Conemaugh. Each of these units are separated by persistent coalbeds. The Brookville Coal overlies the Pottsville Formation, the Upper Freeport coal is the uppermost unit within the Allegheny and the base of the Pittsburgh coal defines the top of the Conemaugh Formation.

In southeast West Virginia and southwest Virginia, Pennsylvanian-age formations include (again in ascending order): the Pocahontas, Lee, Norton, New River, and Kanawha Formations of the Pottsville Group. The Pottsville Group is the approximate time-correlative unit to the Pottsville Formation found in northeast West Virginia. The Allegheny and Conemaugh Groups have no correlative units in southern West Virginia. These younger sediments were removed by erosion. The Pennsylvanian section has a maximum cumulative thickness of 4,350 feet (Arkle et al, 1979).

Throughout the Pennsylvanian system, sandstones are commonly found overlying most of the coalseams (Figure 4). In accordance with accepted nomenclature, these sandstones normally assume the name of the underlying coal. An exception is made when an earlier name has preference, or if the sand is associated with special depositional circumstances.

Pottsville Group

The Pottsville Group found in the Northern Appalachian Basin is time-correlative to a much expanded lithologic series identified in the Central Basin, in a region within West Virginia sometimes referred to as the "Older Mining District". Similar to Mississippian deposition, the primary source of sediments during Pennsylvanian time continued to be south and east of the Appalachian basin area. Again, as with the stratigraphy briefly described in the discussion of Mississippian-age lithologic units, proximity to sediment source areas provided a relative diversity of litho-facies and depositional schemes. The Conemaugh and Allegheny Groups of northern West Virginia are thin, where present, in the southern

portion of the state and not pertinent to the scope of this discussion. Further mention of these units will be made within the discourse on the Northern Appalachian Basin.

This brief review of Pennsylvanian stratigraphy will focus on formational nomenclature as established in published resources. These formations will be discussed in ascending order.

Pocahontas Formation

The Pocahontas Formation consists of feldspathic and micaceous sand, generally low in quartz and often repetitious, massive, slightly argillaceous and locally conglomeratic. Clastic deposition is interrupted by shales, thin coals and associated underclays which were deposited during the periodic and often erratic development of tidal mudflats and swamps occurring along a shifting continental-marine margin.

Coal Stratigraphy

This formation contains several of the most commercially-important coalseams found in the Central Basin, the Pocahontas No.1 through 7 coals. Within this series, the number 3 and 4 seams are the thickest and most extensive (Kelafant et al, 1988). The maximum depth of burial of these coals is approximately 2,500 feet and occurs in Buchanan and Dickenson Counties, Virginia. Extensive mining of the No. 3 coal in Buchanan County, most likely precludes the development of significant (remaining) accumulations of coalbed methane in this area. These coals are generally less than 6 feet thick and often irregularly bedded. The No. 3 Coal is 11 to 15 feet thick in one area. All of these coals are classified as low-volatile, low sulfur, bituminous coals.

Lee Formation (Southwestern Virginia)

The Lee Formation is significant as a prominent ridge-forming quartz arenite. The three arenites within this formation have characteristic massive bedding with cross-lamination, -bedding, and -stratification. They are generally fine to coarse grained and are separated by thin beds of shale, siltstone, sandstone and coal. The massive arenites are predominant near the Virginia/West Virginia state line. These sandstones tongue out to the east and southeast, where micaceous and carbonaceous siltstones and shales are the dominant lithology (Miller, 1974). The Lee Formation is time-equivalent to the New River Formation (described below) found in southwestern Virginia and southwestern West Virginia.

Coal Stratigraphy

Coals of economic importance associated with this formation include the Jaeger/Jawbone. (see New River Formation).

Norton Formation (Southwestern Virginia)

The Norton Formation consists largely of shales and siltstone with only minor amounts of sandstone, coal and underclay. The Norton thickens to the east and southeast where the underlying Lee Formation thins out. The Norton has no direct (lithologic) correlative unit in West Virginia. The Kanawha Formation (discussed later) is, in part, time-correlative to the Norton.

Coal Stratigraphy

Coalbeds within the Norton include the Kennedy, Big Fork, Lower Banner, Upper Banner, Splash Dam, Hagy and Norton coals. To the southeast, in southwest Virginia, the formation contains the Tiller, Jawbone, Raven, and Aily coals plus those already mentioned (Keystone, 1980). The Jawbone coalbed is a high-volatile A to low-volatile bituminous coal

which normally occurs about 100 feet above the Tiller coal, but in some places, these two coals converge into a single unit. The Jawbone is one of the thickest and most extensive coals in the Central Basin and is known to occur in Buchanan, Dickenson, Tazewell, Russel, and Wise counties. Individually, the Jawbone is up to 6.5 feet thick, but can be as much as 15 feet thick when combined with the Tiller coal (Keystone, 1980).

New River Formation (West Virginia and Virginia)

The lithology of the New River Formation is nearly identical to the Pocahontas Formation described above, consisting of interbedded sandstone, siltstone, shale, coal and associated underclay. Sandstones in the New River are fine- to coarse-grained, silty, micaceous, and thinly bedded. The siltstone and shale are gray to dark gray, micaceous, locally carbonaceous, and laminated. The coal and underclays are usually thick and persistent (Miller, 1974). The maximum total thickness of the New River is 1,030 feet, observed in Fayette and Summers Counties in West Virginia (Arkle et al, 1978) and in McDowell County (Keystone, 1980). The formation thins to the northwest, where the combined thickness of the Pocahontas and the New River is only 350 feet (composed of quartz sandstone) near Charleston. Farther north and west, the formation loses its identity in the subsurface.

Coal Stratigraphy

The New River contains sixteen (16) named coal seams and two additional numbered coalbeds (Pocahontas Nos. 8 and 9). Above the lowermost Pocahontas Nos. 8 and 9, the Firecreek (No. 10), Beckley (No. 11), and Sewell (No. 12) coals are commercially exploited. These coals are generally less than six feet thick, although both the Firecreek and Beckley coals are locally up to nine feet in total thickness. These coals are ranked medium volatile, low sulfur coals, and generally equal or surpass the quality of older Pocahontas coals. The higher volatile content of New River coals may enhance their potential as a resource for recovery of coalbed methane gas.

Kanawha Formation

The Kanawha Formation consists of feldspathic, micaceous sandstones (characterized as repetitive, irregular, thin to massive bedded, and locally conglomeratic), shales interbedded with thin carbonates and a total of 16 (named) multibedded coalseams. The Kanawha is 2,100 feet thick in southeastern West Virginia, thinning to 1,000 feet near Charleston, West Virginia. Both the section and the coal seams thin to the northeast and lose identity in the subsurface (Arkle et al, 1978). Most of the coalbeds in the Kanawha are less than 3 feet thick, while the Winifrede and several younger coals range in thickness from 3 to 13 feet.

Coal Stratigraphy

The principal coalbeds within the Kanawha Formation include (in ascending order) the Eagle, Powellton, Campbell Creek, Peerless, Alma, Cedar Grove, Winifrede and Coalberg. Of these, the Winifrede and the Coalberg are the thickest seams and are characterized as high-volatile, low sulfur bituminous coals with numerous shale partings of variable thickness.

Primary Methane Target Area

Kelafant et al (1988) established certain criteria for the evaluation of the production potential of coal-bearing horizons in the Central Appalachian Basin. Three principal coal-bearing units were identified; the Pocahontas, New River/Lee, and the Kanawha/Norton. These formations contain over 80 different coal seams and have a total estimated 80 to 120 billion tons of coal in place. Conditions viewed as essential to the accumulation of in-place methane gas reserves include depth of burial in excess of 500 feet. This overburden would be necessary to prevent the natural discharge of methane into the atmosphere. Prospective target areas would also need to be located at a distance from areas where extensive mining activities (either past or present) would also allow rapid depletion of underground methane

resources. Based on these general criteria and additional research described in the 1988 document, Kelafant determined that only the coals of the Pocahontas and the New River/Lee formations would be prospective in methane gas exploration and production.

While the Kanawha does contain significant and well-documented coal resources, these coalbeds are generally located too close to the surface and have been too extensively mined. Based on the Kelafant study, the Kanawha would not be prospective.

The Pocahontas has a maximum depth of burial of approximately 2,500 feet in Buchanan and Dickenson Counties, Virginia. The Pocahontas No. 3 coal has been extensively mined in this area and should not be regarded as prospective for production of methane gas.

Kelafant identified the following seams within the Pottsville Group (Pocahontas, New River/Lee) as those being the most prospective coalbeds: Pocahontas No. 3, Pocahontas No. 4, Fire Creek, Beckley, Sewell, and Iaeger/Jawbone. The reported depth of burial of these coals in McDowell County, West Virginia ranges from 600 feet for the Iaeger/Jawbone to 2,100 feet for the Pocahontas No. 3.

The lateral extent of the primary target area is generally estimated to contain 4,000 to 5,000 square miles within southeastern West Virginia and Southwestern Virginia (Figure 6).

Coalbed Reservoir Parameters

A number of studies have been prepared to address estimated reservoir parameters for coals in the Central Basin. Research presented in Kelafant (1988) set out the following parametric projections for the Pocahontas-New River coal-bearing interval:

Figure 6. Primary Target Area for Methane Exploration - Central Appalachian Basin (after Adams, 1982).

Net pay (1 to 2.5 feet per coalseam)
Reservoir temperature (60 to 68 degrees Fahrenheit)
Initial reservoir pressure (260 psi to 909 psi)
Permeability (6.9 to 1.9 millidarcies)
Cleat spacing (0.6 throughout the interval)
Porosity (3.0 percent throughout the interval)
Initial water saturation (100.00 per cent throughout the interval)

Additional Published Studies

Additional information has been derived from Zebrowiz et al., 1991. This document concludes that the average (estimated) sorption time for coals in the Central Basin is in the range of 1 to 3 days. The paper also points out that the coalbed methane potential for the Central Basin is very similar to that of the Black Warrior Basin in Alabama. Table 1 and Figure 7 depict a comparison of reservoir distribution and gross characteristics for the Black Warrior, Central and Northern Appalachian Basins.

Coalbed Cleat Development and Orientation

Although overall cleat development in Central Basin coalseams does not exhibit a single predominant, or preferred, orientation, two less dominant trends are apparent. One orientation is northeast-southwest and is likely the direct result of structural deformation associated with Appalachian orogenic events. The second observed trend is essentially north-south. This second trend is most probably related to movement of the Pine Mountain Overthrust Block.

Basis of Comparison	Appalachian Basin		Black Warrior Basin
	Northern	Central	
RESERVOIR AND GEOLOGIC CHARACTERISTICS:			
Gas content (SCF/T)	100-400 (Lower)	205-660 (Similar)	300-500 (Productive)
Permeability (md)	0.1-26 (Lower)	5-27 (Similar)	2-30 (Productive)
Sorption time ($\pm$ day ⁻¹)	60-600 (Slower)	1-3 (Similar)	3-5 (Productive)
Coal rank	hvb	lvb-mvb	mvb-hvb
Gas in place (TCF)	61	5	20
Stratigraphic position	Above Pottsville	Pottsville	Pottsville
Target depth (ft)	800-1,200	1,500-2,500	450-4,000
Hydrostatic gradient (psi/ft)	0.18-0.30	0.35-0.43	0.35-0.43
HISTORICAL TECHNOLOGICAL APPROACH:			
Fracture treatment size	Not state-of-the-art (Smaller)	Not state-of-the-art (Smaller)	State-of-the-art
Completion and production technology	Not state-of-the-art	Not state-of-the-art	State-of-the-art

Table 1. Comparison of Primary Differences between the Appalachian and Black Warrior Basins (after GRI, July 1991).

Figure 7. Comparison of Multiple-Seam Completion Potential in Pennsylvanian-Age Coals in the Black Warrior and Appalachian Basins (after GRI, July 1991).

Groundwater Aquifer Distribution

Mississippian Strata

Development of groundwater resources from Mississippian-age rocks is largely confined to areas located near the outcrop belt in eastern West Virginia. Productive formations include the Mauch Chunk and the Greenbrier Limestone, especially in areas of karst topography. Limited, additional groundwater is produced from the Maccrady Formation and the Pocono Group. Beyond the eastern outcrop belt, Mississippian-age rocks are usually found below the freshwater/saltwater interface.

Pennsylvanian Strata

Pottsville Group sandstones are the most extensive aquifers in southern West Virginia (Arkle et al, 1979). Well yields are reported to range from 1 to 522 gallons per minute (gpm) and average 118 gpm. The freshwater/saltwater interface ranges at depths from 300 to 500 feet (Doll et al, 1960). In Raleigh County, West Virginia, an aquifer test in the Pottsville Group (Wilmoth, 1966) yielded a transmissivity value of 88,000 gallons per day per foot (gpd/ft).

Sandstones overlying the Pottsville are also major aquifers in southern West Virginia. Development of fracture porosity is essential to groundwater production in these rocks.

Conclusions-Central Appalachian Basin

The exploitation of coalbed methane in the Central Appalachian Basin was begun during the 1930's. Information derived from published sources suggests that the potential for additional activity, on a commercially viable basis, is real. Published estimates of methane gas reserves indicate a total of approximately 5 trillion cubic feet may be found

in this area. Documentation of established gas production in the Central Basin indicates that water production is less than 50 barrels of water per day for the average well.

The review of coal-bearing strata presented in this document mentions that sandstone formations are often found in close proximity to many of the individual coalseams. These sands are often very immature in lithologic character and are, in many cases, productive fresh water aquifers in the Central Basin area. With the possible exception of the Lee Formation in southwestern Virginia, none of these sand bodies are massively bedded with wide lateral extent beyond their outcrop. The potential for down-hole disposal of produced fluids should be evaluated in consideration of these factors. The value of each sandstone as either a producing or potential fresh water source should also be evaluated.

The extensive production of coal in this area has had an impact on the availability of commercial reserves of coal-bed methane through loss to the atmosphere. In addition, the acquisition of property by commercial coal operations, either through lease or purchase, will limit the exploration activities of the methane gas producer. This issue is further complicated by the, as yet, unresolved matter of resource ownership.

Some potential does exist in the Central Appalachian Basin for the application of Jack W. McIntyre's patented production process. Additional research is recommended to more fully ascertain the extent of opportunities for commercial operations in this area.

NORTHERN APPALACHIAN BASIN

NORTHERN BASIN STRATIGRAPHY

Pennsylvanian Strata and the Dunkard Group

All commercial coals in the Appalachian basin are produced from the Pennsylvanian strata and the Dunkard group (Figure 8). The Pennsylvanian strata has been divided into

END OF THE LATE PALEOZOIC	
Dunkard Group 335 m + (1100 ft)	Proctor sandstone Windy Gap limestone Nineveh coal Nineveh limestone Jollytown sandstone Jollytown coal Hundred sandstone Upper Washington limestone Lower Marietta sandstone Washington coal Waynesburg sandstone Cassville shale—Elm Grove limestone
Monongahela Group 70-122 m + (230-400 ft)	Waynesburg coal Gilboy sandstone Uniontown coal Benwood limestone Sewickley coal Redstone coal Redstone limestone Upper Pittsburgh sandstone Pittsburgh coal
Conemaugh Group 137-259 m (450-850 ft)	Lower Pittsburgh sandstone Elk Lick coal Ames limestone' Harlem coal Saltsburg sandstone Woods Run limestone' Bakerstown coal Pine Creek limestone' Buffalo sandstone Brush Creek limestone' Brush Creek coal Mahoning sandstone { Mahoning coal Thomton fire clay Uffington shale
Allegheny Formation 30-81 m (100-300 ft)	Upper Freeport coal Bolivar fire clay Upper Freeport sandstone Lower Freeport coal Upper Kittanning coal Washingtonville limestone' Middle Kittanning coal Hamden (Columbiens) limestone' Lower Kittanning coal Lower Kittanning clay Vanport (Ferriferous) limestone' Clarion fire clay
Pottsville Group 15(?)—61 m (50-200 ft)	Homewood sandstone Mercer coal Connoquenessing sandstone Sharon sandstone(?)
MISSISSIPPIAN SYSTEM	

¹Marine

Figure 8. Pennsylvanian and Permian Stratigraphy - Northern Appalachian Basin (West Virginia) (after Arkel et al, 1979).

four groups; the Pottsville, Allegheny, Conemaugh, and Monongahela (Adams et al 1984).

The Dunkard Group is divided into three formations; the Waynesburg, Washington and the Greene Formation. It was first thought that the Dunkard Group was of Permian age and is now considered to include, in part, the Pennsylvanian. The Waynesburg is believed to be of Late Pennsylvanian age and the Washington and Greene formations to be of early Permian age (Adams et al 1984).

Pottsville Group

The Pottsville Group is composed primarily of a sandstone, conglomerate, and siltstone. The western portion of the basin also contains some marine limestones and shales. Some of the source material for the sediments found in the northern portion of the basin is from earlier Paleozoic strata located in the northern highlands. The majority of the sediments, however, were derived from the orogenic belts to the south and east. Except for a small area in Central Pennsylvania, the earlier deposits were buried by the northwest and southwest alluvial fans. The Burgoon sandstone and Mauch Chunk Formation formed sandstone ridges in the central portion of Pennsylvania. The high-alumina Mercer flint clays were formed along these sandstone ridges. The Canadian Shield contributed sediments to the northern portion of the basin which is composed of coarse quartz conglomerates and sandstones. These deposits are important sources of high-purity silica. A limited amount of marine sediments occurred during this time due to the presence of a sandy back barrier which dominated the area during this time (Adams et al 1984).

Allegheny Formation

During Allegheny time, the entire northern Appalachian Basin was submerged. The embayment resulting from the transgression of the seas trended northeast-southwest. Abundant coals can be found in the delta plain environment which occurred on the northern alluvial fan and the alluvial plain environment which occurred on the delta to the south and

east. In central Pennsylvania, towards the eastern portion of the basin, the Llewellyn Formation is a thicker, coarser grained equivalent of the Allegheny, Conemaugh and possibly Monongahela Groups. Throughout the remainder of the basin, the lower half of the Allegheny contains no red beds and few marine or brackish water deposits. The upper half of the Allegheny is entirely nonmarine and contains a fresh water limestone. The principal coal bearing formations of the Allegheny Group are the Brookville-Clarion, the Lower, Middle and Upper Kittanning and the Lower and Upper Freeport (Adams et al 1984).

Conemaugh Group

The Conemaugh Group includes all beds from the top of the Upper Freeport coals to the bottom of the Pittsburgh Formation. The Conemaugh is composed of marine units within the lower delta plain sediments which were deposited as a result of a series of sea transgressions from the northwest. These transgressions resulted in the deposition of both marine and fresh water limestones, redbeds, sandstones, shales and mudstones. Nodular iron is found in the embayment margins of the seas and is responsible for the early development of the iron industry in the Pittsburgh area. However, few important coals are found in the Conemaugh Group (Adams et al 1984).

Monongahela Group

Berryhill and Swanson (1962) divided the Monongahela Group into two formations; the Pittsburgh and the Uniontown Formations. During the Monongahela, the Northern Appalachian Basin was primarily covered by lakes with no marine sedimentation. This lake environment occurred throughout the deposition of the Monongahela Group and continued during the deposition of the Dunkard Group. Some of the most economically important coals of the area were formed as a result of this widespread lake environment (Adams et al 1984).

Dunkard Group

The Dunkard Group lies conformably on the Monongahela Group and is considered to be either Permian age or Pennsylvanian age or both. Berryhill and Swanson (1962) defined the deposition of the Dunkard Group to have started in the Late Pennsylvanian and continued into Early Permian. The deposition of the Waynesburg Formation is considered to have occurred during the Late Pennsylvanian while the Washington and Greene Formations were deposited during the Early Permian. Shale is the most abundant rock type throughout the group. This shale grades from a red shale in the southern portion of the basin to a grey shale in the north. Coals associated with the Dunkard group are thicker in the northern portion of the basin (Adams et al 1984).

Principal Coal-Bearing Formations

The principal coal bearing formations of the Appalachian Basin are Pennsylvanian in age and are within the Pottsville and Allegheny Groups. Coal thicknesses average between 1 and 3 feet with the Pittsburgh formation containing the thickest coal beds. Coal depths range from outcrops to 2,000 feet. Coal rank ranges from high-volatile bituminous to low-volatile bituminous (GRI 3-1990).

Coal resources are estimated at 352 billion tons. Gas content ranges from 3 CF/T at 150 feet to 441 CF/T at 759 feet (Adams et al 1984).

Pottsville Group

The principal coal bearing formation of the Pottsville group are the Sharon, Quakertown, and Lower and Upper Mercer formations. The depositional environment of the Pottsville Group resulted in an intermittent occurrence of coal at varied thicknesses and a limited lateral extent. In some portions of the basin, the coals are known to be only a few feet thick (Adams et al 1984).

The Sharon coal is known primarily from outcrops in the northwestern portion of the basin and occurs infrequently throughout the remainder of the basin. It varies in thickness from a few inches to 4 feet thick. The Sharon coal was once mined commercially but has now been depleted. The Sewell coal located in the Central Appalachian Basin is the lateral equivalent to the Sharon coal and is extensively developed (Adams et al 1984).

The Quakertown and Lower and Upper Mercer Coals are similar to the Sharon coals in that they are only mined locally due to limited areal dispersion or thickness (Adams et al 1984).

Given this limited occurrence, thickness and quality of coal, the Pottsville Group is considered insignificant in the contribution of coalbed methane in the Northern Appalachian Basin (Adams et al 1984).

Allegheny Group

Fifty percent of the minable coals of the Northern Appalachian Basin comes from the Allegheny Group. In ascending order, the most important coals of the Allegheny are the Brookville, the Clarion, the Lower, Middle and Upper Kittanning and the Lower and Upper Freeport formations (Adams et al 1984).

The Brookville coal in Pennsylvania contains high contents of ash and therefore is not mined on a large scale. Thicknesses range from a few inches to 8 feet thick. The Brookville ranks ninth in Ohio's top ten most valuable coalbeds. Brant and DeLong (1960) estimated original reserves of the Brookville coal in Ohio at 450 million tons. Multiple coal seams are present in the Clarion coals. Coal seams range in thickness from 2 to 10 feet in the West Virginia counties next to Pennsylvania (Adams et al 1984).

In some areas, the Lower Kittanning coal is wide spread throughout the Northern Appalachian Basin and in some areas is double or triple bedded. The Lower Kittanning is

an important coal formation of the Allegheny Group. Movable reserves in the Northern Appalachian Basin have been estimated at approximately 20 billion tons (Adams et al 1984). The coal rank of the Lower Kittanning is primarily high volatile A bituminous (84%). The remaining 16 percent is classified as either medium volatile (12%) or low volatile coal (4%) (Headlee and Nolting 1940).

The Middle Kittanning is also widespread throughout the basin and multiple coal bedded. The coal is only locally economical in Pennsylvania and West Virginia. The most economical coals of the formation is in the northern portion of the basin where coal thicknesses are an average of 4.5 feet thick (Adams et al 1984).

The Upper Kittanning is best developed along the eastern portion of the basin. It is not one of the more important bituminous coal fields of Pennsylvania. The coal rank of the Upper Kittanning is primarily high volatile A bituminous (80%) (Adams et al 1984). The remaining 20 % is classified as either medium volatile (16%) or low volatile (4%) (Headlee and Nolting 1940).

The Lower Freeport coals in Pennsylvania attain thickness of up to 16 feet, however, they thin dramatically in a short distance. Indications are that the coal is not just one coal seam but several overlapping coal seam horizons (Adams et al 1984).

The Upper Freeport is one of the most valuable Allegheny coals. It lies at the top of the Allegheny and varies in thickness from a few inches to up to 7 feet thick. The Upper Freeport was originally deposited throughout the basin. It then underwent uplift and erosion which removed it in some areas. In over half of the area that it occupies, the Upper Freeport is three feet thick. The principal mining area is along the basin's southeastern boundary. The Upper Freeport is one of the most valuable coals mined in Ohio (Adams et al 1984). The coal rank of the Upper Freeport is 50% high volatile A bituminous, 37% medium volatile and 13% low volatile coal (Headlee and Nolting 1940).

Conemaugh Group

The Conemaugh Group contains a relative abundance of ash and red shales. The Conemaugh is relatively unimportant in comparison to the Allegheny Group and the Monongahela Group even though it contains up to 30 coalbeds. Only eight of these coals attain a minable thickness in West Virginia. The Conemaugh contains only 3% of West Virginia's original estimated coal reserves. Similar percentages can be seen in Ohio and Pennsylvania (Adams 1984).

Monongahela Group

The thickness of the Monongahela Group ranges from 200 feet thick in Ohio to 400 feet thick in West Virginia. The major coals in this group are, in ascending order: the Pittsburgh, Redstone, Sewickley, and Uniontown (Adams 1984).

The Pittsburgh coal is the most valuable coal in the Northern Appalachian Basin. The Pittsburgh attains its maximum thickness in western Maryland and northeastern West Virginia. It covers an area of approximately 6,000 square miles. As of 1974, 35% of the coal mined in the Appalachian Basin and 21% of the total cumulative production of the United States came from the Pittsburgh coal (Averitt 1975). The coal rank of the Pittsburgh is 97.5% high volatile A bituminous and 2% low volatile bituminous (Headlee and Nolting 1940).

The Redstone coal occurs 30 to 85 feet above the Pittsburgh coal and attains thicknesses ranging from 2.5 to 5 feet thick. The Redstone, however, is thin and poorly developed over most of the Northern Appalachian Basin (Adams et al 1984).

The Sewickley Coal is more prominent than the underlying Redstone coal. Coal thicknesses range from 4 to 8 inches thick in Washington County, Pennsylvania to 5 to 6 feet

thick in southwestern Greene County (Ashley 1928). The Sewickley is commercially mined in Marion, Mongolia, and Marshall Counties of West Virginia (Adams et al 1984).

The coals of the Uniontown have no commercial value due to the thin nature of the seams (Adams et al 1984). However, the Uniontown may hold future reserves when technology advances which will be able to commercial mine these thin coal seams.

Dunkard Group

Only two coals within the Dunkard Group are of economic value; the Waynesburg and the Washington. The Washington is located very close to the surface and probably does not contain any measurable quantities of gas (Adams 1984). Therefore, the Washington will not be considered in this study.

The Waynesburg coal attains thicknesses of 5 to 10 feet thick, of which one fourth to one half consists of clay partings.

PRIMARY METHANE TARGET AREAS

Coalbed methane resources in the Northern Appalachian Basin is estimated to be 61 Trillion cubic feet (Tcf). The primary methane target area in the Northern Appalachian Coal Basin is located in the east central portion of the basin (Figure 9). This target area has been defined based on high gas contents, high coal rank, overburden thickness, high methane mine emission rates and numerous relatively thick coalbeds. The Kittanning Group contains the highest methane resource and is estimated at 30,460 Billion cubic feet (Bcf). The total methane resource for the Northern Appalachian Basin is estimated at 61,335 Bcf. These resources were calculated using estimated average coal thickness and estimated average gas content by county for counties underlain by the individual coalbeds or groups (Table 2). The bulk of the resources are located in the deepest part of the basin, where the coals are thick and of highest rank (Adams et al 1984).

Figure 9. Primary Methane Target Area in the Northern Appalachian Coal Basin (after Adams et al, 1984).

Group or Bed	Approx. Area Underlain by Coal Group or Bed (sq mi)	Methane Resource in Coal Group or Bed (Bcf)
Waynesburg	7,000	2,040
Redstone-Sewickley	8,000	1,635
Pittsburgh	12,600	7,130
Freeport Group	22,800	11,690
Kittanning Group	28,000	30,460
Brookville-Clarion	30,300	<u>8,380</u>
Total		61,335

*Calculated using estimated average coal thicknesses and estimated average gas contents by county for counties underlain by the individual coalbeds or groups.

Table 2. Coalbed Methane Resource Distribution by Coal Group (after Adams et al, 1984).

Coalbed Cleat Development and Orientation

Face cleat orientation in the coal seams of the Northern Appalachian Basin is primarily northwest to southeast. Cleat domains within the basin represent past stress domains and exhibit thickness ranging from 2 meters to several millimeters (Kulander et al 1993).

Groundwater Aquifer Distribution

Give the lack of available information on the groundwater aquifer distribution of the Appalachian Basin, there will be no discussion of the aquifer system.

Conclusions-Northern Appalachian Basin

The Northern Appalachian Basin is a relatively undeformed spoon shaped basin. A series of northeast-southwest trending anticlines and synclines exist within the basin. The basin is located within Pennsylvania, Maryland, West Virginia, Ohio and Kentucky. The areal extent of the basin is 43,000 square miles.

Coal age within the basin is of both Pennsylvanian and Permian age. Coal seams average 1 to 3 feet thick with the thickest coal seams occurring in the Pittsburgh formation (approaching 12 feet thick in places). The major coal seams are in the Allegheny and Monongahela groups. Coal depths range from outcrops to 2,000 feet below ground surface. Coal rank is high volatile bituminous to low volatile bituminous and coal resources are estimated at 353 billion tons.

Coalbed methane resources are estimated at 61 Tcf of gas in place. The potential economics of producing coalbed methane from the basin is considered high. However, legal issues such as who owns the rights to the coalbed methane gas has limited the development of the Northern Appalachian basin from the standpoint of coalbed methane

gas production. Further issues such as disposal problems associated with production water has further limited the production of coalbed methane gas from the basin.

The potential applicability of Jack W. McIntyre's patented tool was not evaluated for the Northern Appalachian Basin due to the lack of information on the basin's groundwater aquifer distribution.

REFERENCES

- Adams, M. A., et al, "Geologic Overview, Coal Resources, and Potential Methane Recovery from Coalbeds of the Northern Appalachian Coal Basin - Pennsylvania, Ohio, Maryland, West Virginia, and Kentucky, in Coalbed Methane Resources of the United States", AAPG Studies in Geology Series #17, 1984.
- Arkle, T., Jr., Beissel, D. R., Larese, R. E., Nuhfer, E. B., Patchen, D. G., Smosna, R. A., Gillespie, W. H., Lund, R., Norton, C. W., and Pfefferkorn, H. W., "The Mississippian and Pennsylvania (Carboniferous) Systems in the United States-West Virginia and Maryland", USGS Professional Paper 1110-D, 1979.
- Ashley, G. H., "Bituminous Coal Fields of Pennsylvania", Pennsylvanian Geological Survey, 4th Series", Bulletin M6 Pt. 1, p. 241, 1928.
- Averitt, P., "Coal Resources of the United States, January 1, 1974", United States Geological Survey Bulletin 1412, p. 131, 1975.
- Dally, J. L., "The Stratigraphy and Paleontology of the Pocono Group in West Virginia", New York, Columbian University, Ph.D. thesis, 248 p., 1956.
- Dennison, J. M. and Wheeler, W. H., "Stratigraphy of Precambrian through Cretaceous Strata of Probable Fluvial Origin in Southeastern United States and Their Potential as Uranium Host Rocks", Southeastern Geology Special Publication #5, 1975.
- Doll, W. L., Wilmoth, B. M., Jr., and Whetstone, G. W., "Water Resources of Kanawha County, West Virginia", West Virginia Geological and Economic Survey Bulletin N. 20, 1960.
- Headlee, A. J., and Nolting, J. P., Jr., "Characteristics of Movable Coals of West Virginia", West Virginia Geological Survey Report 13, p. 272, 1940.
- Hunt, A. M., and Steele, D. J., "Coalbed Methane Development in the Appalachian Basin Quarterly Review of Methane from Coal Seams Technology", Gas Research Institute, pp. 10-19, 1991.
- Kelafant, J. R., Boyer, C. M., and Zuber, M. D., "Production Potential and Strategies for Coalbed Methane in Central Appalachian Basin", SPE Paper 18550 presented at the 1988 Eastern Regional Meeting, Charleston, West Virginia, November 1-4.
- Keystone, "Keystone Coal Industry Manual: New York", Mining Information Services, McGraw-Hill Mining Publishing, 1980.

Kulander, B. R., Dean, S. L., "Coal-Cleat Domains and Domains Boundaries in the Allegheny Plateau of West Virginia", The American Association of Petroleum Geologists, Volume 77, #8 (August 1993), p. 1374-1388, 1993.

Miller, M. S., "Stratigraphy and Coalbeds of Upper Mississippian and Lower Pennsylvania Rocks in Southwestern Virginia", Virginia Division of Mineral Resources, 1974.

Quarterly Review of Methane from Coal Seams Technology, Gas Research Institute, Volume 7, Number 3 (July-September 1989), March 1990.

Wilmoth, B. M., "Hydraulic Properties and History of Development of Lower Pennsylvanian Aquifers", West Virginia Academy of Science: Proceeding v. 39, pp. 337-342, 1967.

Wilmoth, B. M., "Ground Water in Mason and Putnam Counties, West Virginia".

DATE

FILMED

5 / 10 / 94

END