SPE

Society of Petroleum Engineers of AIME

SPE 8359

EVALUATION OF GAS BEARING COAL SEAMS

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This paper was presented at the 54th Annual Fall Technical Conference and Exhibition of the Society of Petroleum Engineers of AIME, held in Las Vegas, Nevada, September 23-26, 1979. The material is subject to correction by the author. Permission to copy is restricted to an abstract of not more than 300 words. Write 6200 N. Central Expy., Dallas, Texas 75206.

ABSTRACT

Methane recovery from coalbeds is one of several unconventional gas resources in the United States currently under evaluation by DOE and industry. The methane gas associated with both minable and unminable coal seams represents a sizable resource. Approximately, 19.8 Tm^3 (700 Tcf to 800 Tcf) of gas is locked in these seams, of which an estimated 8.5 Tm^3 (300 Tcf) is believed to be contained in minable bituminous coalbeds. No universally accepted estimate exists for the recoverable portion.

To delineate the coalbed resource it is necessary to acquire, analyze and evaluate coalbed methane data from various candidate seams located in the Illinois Basin, Piceance Basin, Arkoma Basin, Rocky Mountains and other coal bearing regions. Several diagnostic techniques have been successfully employed to evaluate potential coalbed gas reservoirs. These techniques are borehole geophysical logging, conventional coring, sidewall coring and drill stem testing. Recent advances in computerized analysis of logging measurements provide reliable information for coal seam evaluation. Petrophysical results are correlated with data from core desorption tests and DST flow, pressure and temperature measurements. This coordinated evaluation program has yielded significant information on the characterization of these coalbeds and their gas content. Experience gained in employing these techniques to coal is presented.

INTRODUCTION

An integral feature of the joint DOE/METC-Industry Methane Recovery from Coalbeds Project (MRCP) is to construct a data base which will provide essential information on quantity and quality of coalbed methane, its distribution and its production characteristics.[1] This goal can be accomplished by evaluating each individually encountered coal seam in the candidate wells using conventional reservoir assessment methods.

References and illustrations at end of paper.

Methane, the major component of natural gas, is generated during the geological formation of coal and frequently is trapped in the coal and associated strata. As might be expected, the distribution of existing coal resource data is influenced more by local economics than by the actual concentration of total coal deposits. The most accessible deposits have been mapped and defined in preference to the less economical minable and unminable coal seams which lie at great depths. Figure 1 presents an outline of the bituminous and subbituminous coal fields located in the conterminous United States. TRW, Inc., Energy Systems Group, as the integrating contractor for the Methane Recovery from Coalbeds Project, has prepared plans in conjunction with DOE/METC to examine 9.842 x 10^{11} m^2 (380,000 square miles) of coal bearing rocks. It has been estimated that 19.8 Tm^3 (700 trillion cubic feet) of methane is contained in those rocks. The distribution of the gas content in the coals to be tested is unknown. The initial evaluation efforts have concentrated on 2.072 x 10^{11} m^2 (80,000 square miles) of this area where the probabilities of finding, producing and utilizing the methane are high. A cooperative drilling, coring, logging and well testing program was initiated to extend the existing data base.

The basins selected for immediate testing are listed in Table 1. The selections were guided by the following criteria.

- Physical and chemical characteristics of coal (i.e., fixed carbon, percent volatiles, percent sulfur, etc.) - Higher rank coals generally contain more methane.
- Seam depth [East: ≥ 122 m (400 ft); West: ≥ 213 to 244 m (700 to 800 ft)] - Deeper coals are more likely to have retained the methane.
- Total effective coal thickness (East: ≥ 6 m (20 ft) for high rank; West: ≥ 9 m (30 ft). Higher total production per well possible on basis of multiseam completion.

- Individual seam thickness [minimum of 1.5 to 3 m (5 to 10 ft) for shallow beds; multiple coalbeds considered as one if separated by permeable rock units] - Minimize need for multiple fracturing.

- Areal extent (contiguous basin) - Allow extrapolation of results to a wider area.

Based upon the criteria, portions of major basins were selected as the targets for initial resource delineation activities. A total of 80 wells will be evaluated for coalbed methane content, 32 wells have been drilled and tested as of August 1, 1979.

This paper discusses the test activities and results from four selected wells and the problems associated with evaluating the gas bearing coal seams (Fig. 1). Table 2 presents a site summary for each of the four test wells. Various methods were employed to evaluate the coal seams and to test for coalbed methane occurrence. The tools used to perform the data acquisition are classified into four main test categories. Utilization of well logs is also discussed.

- Geophysical Well Logging Tools
  - Resistivity devices (conductivity, and electrical resistivity logs)
  - Self-potential device (SP log, water resistivity and shale content)
  - Nuclear radioactivity devices (density, neutron, gamma-ray, gamma-ray spectral logs)
  - Acoustic device (travel time measurements)
- Mud Logging Tools
  - Sample traps (shale shaker, Buoy line trap)
  - Gas chromatograph (gas composition)
  - Drilling recorders (penetration rate, weight on bit)
- Coring Tools
  - Conventional core barrels (lined and unlined barrels)
  - Sidewall coring device (multiple shot)
- Flow Testing Tools
  - Drill Stem Test Arrangement
  - Production Testing

TECHNICAL APPROACH

The traditional approach in the coal industry for evaluating coal prospects consists mainly of drilling a large number of shallow core holes. Sample cuttings and small diameter cores are described by geologists. The various properties of the recovered coals are measured in the laboratory. These data were used by the coal companies for mapping, volumetric estimates and economic evaluation of the seams.

The oil and gas industry prepares similar economic appraisals for hydrocarbon reservoirs by drilling, for the most part, only a few wells. This well-established oil field experience and technology can be utilized to acquire data on the deeply buried coal seams and will lead to much improved evaluations, especially when gas is associated with the coal seams.

Wells are catagorized in the MRCP on the basis of the kind of testing permitted as Type I, Type II, or Type III. Type I wells are conventional oil or gas wells being drilled to potential reservoirs beneath the coal and are available only for short-term (one or two day) tests. Type II wells are those wells drilled for any other purpose that is scheduled for abandonment. All activities with Type II wells assume that the coal is cased and there is a good cement bond between casing and coal zone. Type III wells are those drilled expressively for completion as a production well from coalbeds. They can be used for an entire suite of tests.

The technical approach implemented in this project is one which will attempt to establish for each coal seam the petrophysical, chemical (proximate and ultimate analysis), fluid saturations, fracture development and orientation, pressure, temperature and lithological characteristics. These parameters are best determined by geologic mapping, drilling, coring testing and logging the wells. For a delineation of the total resource the acquired data is broken into two broad categories; resource determination tests and methane producibility tests.

Resource Determination Tests

Primary elements to be tested for the determination of the character of the coalbed methane resource are:

Coal Rank. There are indications that gas content increases with rank, but this relationship is inconclusive, and there are some notable exceptions. Depth of burial and degree of strata deformation may have a more important influence than rank on gas migration from the seam by reducing porosity and permeability. Rank is determined from the proximate and ultimate analyses of coal collected by core drilling or sidewall coring.

Specific Gas Content. Coal samples collected by conventional coring and by sidewall coring are subjected to gas desorption testing and are analyzed for hydrocarbon content. The gas volume per unit weight of coal provides an upper limit for gas production, but is not by itself an indicator of production rate. This rate is controlled by permeability, coal seam gas pressure, and other characteristics of the coal. The methane adsorption capacity of coal are determined by desorption testing of cored coal samples.

Gas Pressure. Drill stem tests are conducted to ascertain the pressure of gas within the coal seam. In-situ gas pressure is the major factor other than permeability influencing flow rate. Pressure is related to a number of variables,

but is primarily a function of overburden thickness. Local pressure can result from deformation or folding of strata which tend to compress the formation near the top of the arch and thicken or expand the excess into the limbs. The seam pressure may also be hydrologically controlled.

Seam Thickness. Coal seam thickness can be determined by examination of core samples, well cuttings and well logs. Seam thickness may be an important indicator of production potential. Although total coal thickness may also be a factor due to potential for multi-seam completions, the relationship between individual seam thickness and total coal thickness may not be correlative in an area of interest. Flow rates generally are higher from a single thick seam than from several thinner seams of equal thickness. The reasons are not completely understood, but the volume of connected pore space is probably higher in thicker seams, and fraction losses are lower due to a smaller flow surface area.

Overburden Characteristics. Core material, well logs, and seismic data are analyzed in order to evaluate overburden characteristics pertinent to the coalbed methane resource. General indicators are that gas content increases with thickness of overburden. Classic stratigraphic traps of the size and type forming large oil and gas reservoirs are infrequently found in coal seams, similar features, on a smaller scale, could control the gas content in coal seams and should be considered.

Producibility Tests

Primary elements to be tested for determinating producibility of the coalbed methane resource are:

Coal Permeability. This is a direct measure of the ability of coal to conduct fluids or gas through interconnected void spaces. Core samples can provide good indications of permeability, but must be viewed as conservative estimators since formation permeability often is dramatically higher than indicated by individual samples, and because the samples usually are not large enough to represent the larger fracture systems. Data on the larger fracture systems are obtainable from water or gas injection or natural flow testing. Gamma ray spectral logging appears to assist in defining fractured intervals.

Liquid Saturation. Moisture content of coals is a measure of the amount of water relative to the void space in the coal seam and is obtained from laboratory analysis and well logs. Increasing moisture content in the coal pore spaces reduces the apparent permeability to gas due to friction. Data on the effects of water on gas production are obtainable from pumping tests.

Face and Butt Cleat Orientation. Face cleats are those fractures perpendicular to the fold axis and are the primary source of permeability in coal seams. Butt cleats tend to be discontinuous and unconnected while face cleats are long and fairly continuous fractures. These data are obtainable from in-mine examination and by studying regional stress patterns and oriented cores from wells drilled in unminable areas.

Flow-Testing. Primary criterion of success for methane production is the gas flow rate from the wells. Flow tests (cubic feet per day over a 10- to 15-day period) will be considered before and after stimulation to observe the effects of stimulation and the correlation between coal permeability and unstimulated flow rate.

Because water saturation of the coal has a hindering effect on gas production, it will be minimized by pumping to permit maximum gas flow.

In a few wells, the effect of wellhead pressure on flow will be determined. In conventional gas reservoirs, wellhead pressure can be maintained above one-half or three-fourths of formation pressure without greatly reducing gas production rate.

Coal Seam Evaluation from Well Logs

Inasmuch as geophysical well logs can be easily procurred for each well, this method provides one of the surest ways of obtaining the necessary coal seam information.

Coal exhibits characteristic log responses which can be applied to locate, define, and evaluate coal seams. A large number of sophisticated logging tools and locally applicable empirical correlations between specific coal parameters and log responses have been developed over the last three decades. Recently, more basic quantitative log-derived evaluation concepts have become available.[2,3,4,5,6]

Digital well log analysis is based on the logging suites available, two and three dimensional crossplot concepts, etc. It provides in-situ information as to the lithology, coal seam thickness, carbon, ash, and moisture content. Furthermore, the clastic constants of the roof and floor rocks, such as Young's Modulus, Bulk Modulus, Shear Modulus, and Poisson's Ratio, can be calculated from logging parameters (Table 3). Well log responses in coal seams include:

Caliper (Borehole Size): Depending on drilling operations and type of coal, seams may exhibit severe washouts or may still be close to gauge. Occasionally, some coal seams tend to cave toward the floor rock only.

Spontaneous Potential (SP-Curve): Due to some permeability in some coals, occasionally seams are characterized by an SP-deflection similar in shape to the one across permeable clastic sediments.

Gamma Ray (Natural Radioactivity): Coal seams usually exhibit low total natural radioactivity. Presence of thin dirt partings, consisting of various clay minerals, will increase the measured natural radioactivity. Under localized and proper conditions (i.e., absence of high and drastically varying kaolinite concentrations) the ash content may be empirically determined from the gamma ray log.

Presence of large and drastically varying clay mineral content, such as the potassium-deficient kaolinite and/or localized secondary enrichment of uranium (UO_2) under prevailing reducing conditions (i.e., negative Eh-potential), will make such gamma-ray-derived ash content determinations totally unreliable. Thorium-derived correlations using the Spectralog® (spectral gamma ray logging), however, are still applicable.

Spectral Gamma Ray Logging; such as the Spectralog[7], provides continuous records of the total number of gamma rays measured and the background corrected count rates for potassium, uranium, and thorium. Total counts are recorded in the lefthand track in either counts/minute or API units. In the right-hand track of the Spectralog®, the potassium (K) curve is recorded in percent, uranium (U) in parts per million, and thorium (Th) in parts per million. Hence, the presence and variation of radio elements, such as K, U, and Th in the subsurface can be investigated in open and cased boreholes.

Application of the spectral gamma ray log to ash content estimates based on K and particularly Th-content, roof and floor rock evaluation, detailed stratigraphic correlations, definition of depositional environment, etc., is useful.

Numerous coal seams, particularly low rank coals, are known to excessively high uranium content. This includes: Eocene sub-bituminous coal at Rosa, Yugoslavia (≤ 300 ppm U); subbituminous Hungarian coals (≤ 100 ppm U): coal at Wackersdorf, West Germany; Trimmelkamm, Austria (≤ 0.5%): Sweetwater County, Wyoming; Paleocene lignite in Harding County, South Dakota; etc. High uranium content of coals is well known from the U.S.A., U.K., France, Germany, Austria, Hungary, Czechoslavakia, Yugoslavia, U.S.S.R., etc. In general, coals have been encountered with U-concentrations up to a few thousand ppm, but concentrations above 100 ppm are not too common.

Laboratory investigations have shown that low rank coals remove over 98% of U irreversible from solution, probably in metallo-organic form. In contrast, clays, shale, and limestone will retain only up to 28% of U in solution.

Occasionally, carnotite-stained coal (i.e., exhibiting radium {Ra} content) or zirconium content (i.e., ≤ 100 ppm Hf {hafnium} may be encountered.

Uranium may enter coal seams with migrating subsurface waters in the form of $Na_2\{UO_2(CO_3)_2\}$, the soluble sodium uranyl dicarbonate, or $Na_4\{UO_2(CO_3)_3\}$, the sodium uranyl tricarbonate complex.[8] In the somewhat acidic environment of the coal seams these complexes decompose and the uranium easily absorb on the coal with subsequent reduction to UO_2. Depending on the silica content of the subsurface waters either the minerals uranite or coffinite will be formed.

Resistivity. Depending on the type of medium in the borehole (air, gas, water) and the thickness of the coal seam (a consideration for the vertical resolution of the logging tool), several resistivity (conductivity) logs can be used, including induction, laterolog, pad devices, or single electrode tools.

Coal is very resistive. Generally speaking, coal resistivity is a function of both the physical and petrographic properties of the subject coal, the mineral composition in the seam, and the degree of methamorphism.

Empirical correlations of coal seam resistivity and ash content or volatile matter can be derived.

Density. Density logs are excellent for coal identification and evaluation. Generally speaking, the densities of coals range from 1.4 g/cc to 1.8 g/cc for anthracite, 1.2 g/cc to 1.5 g/cc for bituminous coal, and 0.7 g/cc to 1.5 g/cc for lignite.

Density-derived estimates of the ash content are frequently applied. The factors influencing ash determination as a function of density are:

- Type of mineral matter associated with the coal.
- Moisture content.
- Rank.
- Maceral composition.
- Gas saturation.

Acoustic Properties. Coal exhibits very high acoustic travel time (Δt) values, with the actual values depending on the quality and rank of the coal. Values for Δt in coal[9] as follows: lignite beds: $\Delta t_{coal} \approx 140$ to 170 μsec/ft, bituminous coal: $\Delta t_{coal} \approx 100$ to 150 μsec/ft, and anthracite coal exhibits Δt values lower than for bituminous coals.

Similar to shales, compaction effects are known to occur in coal seams. For example, a reduction in Δt-values of 0.5 μsec/ft per 100 feet, depth increase has been observed in French coal deposits.

Neutron Response. High carbon content of coals drastically moderates neutrons. This results in very low counting rates measured at the detector of the neutron logging device, the result being a measured porosity index which usually exceeds 50 porosity units.

An example of some crossplot possibilities of data from the Twin Arrow Well No. 2 are illustrated in Figs. 2, 3, 4 and 5. These crossploting techniques are used to characterize the coal seam properties such as carbon, ash and moisture content as well as the host lithology. It should be noted that not all crossplots will be as helpful, for example, as the density versus the acoustic log plot. Pertinent data are marked on each of these crossplots which are quite self-explanatory.

Figure 6 shows the lighologic variations over the geologic section 168 to 259 m (550 to 850 ft), including the stratigraphic location, thickness, and the ash-carbon-moisture content of the seams in the Twin Arrow No. 2 well. Data from the spectral gamma-ray log showed that these coal seams have low radioactivity.

TEST RESULTS

Much of the data reported in this paper are preliminary inasmuch as the analyses are still in

progress. Discounted gas deliverability has been modelled for several of these tests and is discussed in terms of a production characterization factor, ø, which is defined as the cumulative average discounted production for a ten year period. The discount factor chosen was 15% per year.[10]

Brown Estate No. 1-2 Well (Arkoma Basin)

Sidewall coring and drill stem testing were conducted on a well drilled and logged by Arkla Exploration, the Brown Estate #1-2, in Pittsburg County, Oklahoma. This well was drilled in the Arkoma Basin and the cooperative work lead to the sidewall core desorption and drill stem testing of the Hartshorne Coal of Pennsylvania age at about 823 m (2700 ft). On the basis of depth and coalbed description as derived from the well logs, it is likely that the coalbed encountered at 831 m (2726 ft) is the Upper Hartshorne coal. The shallower seams are likely thin coals in the McAlester Shale. No conventional coring was planned or conducted.

Forty-eight (48) sidewall core shots were taken in the intervals 558.7 to 559 m (1833.0 to 1834.0 ft), 580.0 to 580.9 m (1903.0 to 1906.0 ft), 647.4 to 649.5 m (2124.0 to 2131.0 ft), and 823.9 to 832.7 m (2703.0 to 2732.0 ft) identified on the well logs as being coal-bearing intervals. Two (2) sidewall cores were recovered in first interval, three (3) in the second, seventeen (17) in the third interval, and eighteen (18) in the deepest interval. Gas contents observed ranged from 2.27 to 4.09 cc/gm (73 to 131 ft^3/ton) of coal.

Two (2) DST's were planned, one in the Upper Hartshorne Coal and one in the coal at about 646 m (2120 ft). The DST of the Hartshorne, conducted over the interval 823 to 835 m (2700 to 2740 ft) showed flow of 1.43 m^3 (9.0 barrels) of water per day at a shut-in pressure of 4937 kPa (716 psig). The average permeability calculated over the interval was 4.5 md. The second DST was cancelled at Arkla's request because of risk of sticking tail pipe below the packers during the test.

Using weighted average values for gas content, the gas-in-place is estimated at 1.4 Bcf/640 acres. Using maximum permeability of 1.0 md and maximum relative permeability curve and maximum permeability of 0.1 md and minimum relative permeability curve, a range of discounted gas deliverability, ø, of 1132.7 Mm^3 (40,000 Mcf) and 99.1 Mm^3 (3500 Mcf), was calculated.

Henderson No. 2 Well (Illinois Basin)

Testing of the Hagen Oil Company, Henderson No. 2 well, in Clay County, Illinois (Type I), provided gas content and reservoir parameter data for the Illinois Basin coals of Pennsylvanian age. Fifty mine meters (194 ft) of core was cut between 301.7 to 460.2 m (990 feet and 1510 ft). Coal was encountered at the following depth intervals: 302.3 to 303.3 m (992 to 995 ft) - Danville No. 7; 315.2 to 315.8 m (1034 to 1036 feet) - Herrin No. 6; 327.4 to 327.8 m (1074 to 1075.5 ft) - Briar Hill No. 5A; 331.9 to 332.4 m (1089 to 1090.5 ft) - Harrisburg No. 5; and 412.1 to 412.2 m (1352 to 1352.5 ft) the Seelyville coals.

Desorption of eight (8) conventional core samples yielded gas contents ranging from 0.26 to 1.25 cc/gm (8.3 to 40.0 ft^3/ton) of coal. While the sample from the deepest coal, the Seelyville, had the highest gas content, the next highest was from the shallowest coal sampled. There appears to be minimal correlation of gas content with depth in these samples. However, there appears to be a linear relationship existing between the desorbed gas and the heating values on as received basis for the five main seams. Higher the heating values lower the amount of desorbed gas. Sidewall core desorption analyses were conducted on one (1) coal sample [302.5 to 302.7 m (992.5 to 993.0 ft) - coal and gray shale] and on two (2) shale samples [302.8 to 303.1 m (993.5 to 994.5 ft) - gray shale and 328.4 to 328.7 m (1077.5 to 1078.5 ft) - carbonaceous shale to dark gray shale]. The coal contained 0.87 cc/gm (27.7 ft^3/ton) gas in place while the shales contained 1.73 and 0.59 cc/gm (55.2 and 19.0 ft^3/ton), respectively.

Three (3) DST's were attempted to attempt to ascertain reservoir parameters for the respective coal bearing intervals. In this well, it was possible to set packers to test a 3.7 m (12 foot) interval so only relatively small portions of the non-coal section were tested. The intervals tested were 409 to 412.7 m (1342 to 1354 ft), the Seelyville interval; 326.4 to 330.1 m (1071 to 1083 ft), the Briar Hill No. 5A interval; and 313 to 316 m (1026 to 1038 ft), the Herrin No. 6 interval. The last test was misrun when the tool plugged. The other two showed the reservoirs to be normal hydrostatic pressure and with limited permeability (<2 md). No gas was observed in either successfully performed test.

An estimate of gas-in-place based on eight (8) feet of coal thickness is only 200 MMcf/640 acres. With the extremely low permeability of the two seams tested, the deliverability must be less than 0.283 Mm^3/day (10 Mcf/day). A realistic value for ø is in the range of 28.3 to 56.6 Mm^3 (1000 to 2000 Mcf).

Twin Arrow No. 2 Well (Piceance Basin)

A second Type I test was conducted in a well being drilled by Twin Arrow Drilling, the C&K #4-14 well, on the Douglas Creek Arch. Of the series of tests planned for this well, only the coring and desorption of the shallow coal seams could be completed as the hole was lost before reaching the deeper coal seams at about 640 m (2100 ft). One-hundred and fifty feet of conventional core were cut from which five (5) coal samples, two (2) carbonaceous shales with coal samples, and two (2) carbonaceous shale and/or siltstone were collected for desorption analysis (Table 4). Figure 6 presents the coal log for 168 to 259 m (550 to 850 ft).

Gas-in-place estimates utilizing gas content data from Fuelco and Twin Arrow Well No. 1 and an average thickness of 1.9 m (6.2 ft) yield approximately 750 MMcf/640 acres. This low gas content coupled with no flow from the tests of Twin Arrow #1 indicates minimal deliverability.

Confidential Well - Colorado

Tests on a Confidential well (Type I) in Colorado yielded data on coals from the Upper Cretaceous Mesaverde Group between depths of about

1112 to 1519 m (3650 and 4985 ft). Figure 7 presents the lithologic variation over the geologic section 1417.3 to 1521 m (4650 to 4990 ft). The ash, carbon and moisture content is given for 11 of the 12 seams. Strength index of the "floor" and "roof" rocks is also shown in Fig. 7. Conventional coring was planned to provide coal samples for desorption from three coal rich zones in the Mesaverde Group. A total of 4.94 m (16.2 ft) of coal in 8 different intervals was encountered in 42.4 m (139 ft) of core. Six tenths of a meter (2 ft) were cored in the upper coal zone [1113 to 1113.3 m (3652.0 to 3652.6 ft) and 1120.0 to 1120.4 m (3674.7 to 3676.1 ft)], 0.49 m (1.6 ft) in the middle zone [1195.7 to 1196 m (3923.0 to 3924.1 ft), 1199.9 to 1200.0 m (3937.0 to 3937.2 ft) and 1203.3 to 1203.4 m (3947.9 to 3948.2 ft), and 384 m (12.6 ft) in the lower zone 1417 to 1420.3 m (4649.0 to 4659.8 ft), 1420.6 to 1420.7 m (4660.8 to 4661.0 ft), and 1433.9 to 1434.4 m (4704.4 to 4706.0 ft)]. The Mesaverde coals are discontinuous, lenticular bodies which are difficult to correlate under good conditions. The nearest well control which was logged through the coal zone was six miles from this test, making any attempt at correlation questionable at best. Borehole geophysical logs on this hole indicate the presence of approximately 45.7 m (150 ft) of coal in the well.

Methane desorption of the 14 conventional core samples is still in progress but the preliminary data indicate methane contents of most samples well in excess of 200 cubic feet per ton of coal. Some of these samples have been desorbing significant volumes of methane for more than six months.

Twenty-six sidewall cores were obtained from this well. Eleven coal samples and one very carbonaceous shale were selected for complete desorption by GeoChem Research to provide additional gas content data on seams observed on logs. These samples yield gas contents ranging from less than 3.1 cc/gm (100 ft^3/ton) for carbonaceous shale to about 6.6 cc/gm (210 ft^3/ton) for coal at 1482.6 m (4864 ft). Attempts were made to collect sidewall cores from each interval cored by conventional methods. However, the high percentage of misfires and sidewall core bullets lost in the hole stymied this effort. While these gas contents are lower than those being determined for conventional core samples, it must be noted that they are within the same range. Table 5 presents the gas desorption data for this well.

Two drill stem tests (DST) were conducted in an attempt to gain additional information on the reservoir parameters of coalbeds. The tests were over intervals significantly thicker than the coalbeds of interest and as such cannot be considered to be representative of the coalbeds alone. The tests were conducted over depth intervals of 1128 to 1158 m (3700 to 3800 ft) and 1412 to 1437 m (4634 to 4714 ft). DST testing of the upper interval 1097 to 1128 m (3600 to 3700 ft) flowed gas to the surface at about 4 oz pressure. Seventy-eight meters (256 ft) of mud cut water was recovered. Pressure extrapolates to 11321 kPa (1642 psia) with a pressure gradient of 9.95 kPa/m (0.44 psi/ft). Testing of the lower interval 1412 to 1437 m (4634 to 4714 ft) also flowed trace of gas to surface. Recovery totalled 1351 m (4433 ft) of fluid including 450 m (1478 ft) of gas and mud cut water, and 450 m (1477 ft) of gas cut water. The formation fluid was fresh with a chloride content of 700 ppm. Extrapolation of initial shut-in pressure build up indicates a maximum reservoir pressure of 13,982 kPa (2028 psig) with a pressure gradient of 9.95 kPa/m 0.44 psi/ft. This test indicates a permeability of about 1450 md for the 4.57 m (15 foot) interval reported by Johnston and of about 1000 md for the 6.70 m (22 foot) interval reported by INTERCOMP on their analysis of Johnston's test data.

Estimates of gas-in-place for the upper zone range from 1.8 to 4.0 Bcf/640 acres. These parameters give ranges of discounted gas deliverability, ø, of 453 Mm^3 to 1840 Mm^3 (16,000 Mcf to 65,000 Mcf). These calculations are based on the assumption that only the 3.66 m (12 feet) of coal in the 30.5 m (100 ft) interval tested contribute to the parameters utilized in the calculation of deliverability.

Estimates of gas-in-place from the lower zone yield 6.6 Bcf/640 acres. The high permeability determined from the DST is outside the ranges investigated for the model, so no effort was made to calculate discounted gas deliverability, ø, for this interval.

In light of the relatively high gas contents and the thickness of the coal, additional testing is anticipated in this well in 1979. Plans have been made to complete one coal interval, 1482 to 1485 m (4863 to 4873 ft), utilizing artificial stimulation (fracturing) if necessary, to equip the well for a long term production test, and to conduct a long term production test if water and gas flow conditions justify such.

ACKNOWLEDGEMENTS

The preparation of this paper was performed under DOE contract (DE-AC21-78MC08089).

SUMMARY

Resource Engineering field activities are beginning to provide the necessary data base so that the nation's gas resource can be accurately evaluated for both minable and unminable coal seams. The data presented in this paper is an overview of the properties of the gas bearing coal seams encountered in four cooperatively drilled Type I wells.

Well logs have provided a fast and economical reconnaissance of each well. Logs are used to provide continuous data on the thickness of the coal seams, the in-situ determination of the ash-carbon-moisture content, the relative strength properties of the floor and roof rock, and the geologic character of the drilled stratigraphic column. Control of the driller's depth, the coring depth and the interval cored is also provided by logging information. Logging suites applied to these tests depended upon on how wells are being drilled (air, mist or fluid).

Conventional and sidewall cores provide the necessary gas desorption data and the gas composition. Well tests attempt to define reservoir conditions and producibility of the coalbed methane.

The following observations were made on the four wells.

- Thickness of the coal seams encountered in these wells ranged from approximately 0.15 to 4.87 m (0.5 to 16 ft).

- Range of the gas content as determined by the direct desorption method ranged from 0.26 to 10.6 cc/gm (8.3 to 340 ft^3/ton) in conventional core samples, and from 0.59 to 6.6 cc/gm (19 to 210 ft^3/ton) for sidewall core samples.

- Calculation of gas in place ranged from 200 MMcf/640 acres in the Henderson No. 2 well (Illinois Basin) to 6.6 Bcf/640 acres in the Confidential Well in Colorado.

- Discounted gas deliverability (ø) values ranged from a low of 28 Mm^3 (2000 Mcf) in the Henderson No. 2 well (Illinois Basin) to 1840 Mm^3 (65,000 Mcf) in the Confidential Well in Colorado.

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TABLE 1
Basins Selected For Immediate Evaluation.

BASIN	TARGET AREA Mi^2	m^2
Green River	21,200	5.4908×10^{10}
Powder River	12,800	3.3152×10^{10}
Illinois	9,100	2.3569×10^{10}
Arkoma	5,300	1.3727×10^{10}
San Juan	4,900	1.2691×10^{10}
Bellingham	400	0.1036×10^{10}

TABLE 2

Site Summary of Well Test Activities.

WELL	BASIN	CO-OPERATING COMPANY	TEST SITE LOCATION					COAL SEAMS	WELL TEST ACTIVITIES			
			STATE	COUNTY	SEC.	TW	RANGE		LOGGING	MUD LOGGING	CORING	FLOW TESTING
BROWN-ESTATE NO. 1-2	ARKOMA	ARKLA EXPLORATION CO.	OK	PITTSBURG	2	T6N	R13E	LOWER HARTSHORNE	D. INDUCTION LATEROLOG CALIPER DENSITY SONIC SP γ-RAY	–	SIDEWALL	DST
HENDERSON NO. 2	ILLINOIS	HAGEN OIL CO.	IL	CLAY	19	T3N	R8E	DANVILLE (No. 7) HERRIN (No. 6) BRIAR HILL (No. 5A) HARRISBURG (No. 5) SEELEYVILLE COALCHESTER (No. 2)	D. INDUCTION LATEROLOG DENSITY DIPMETER SONIC CALIPER γ-RAY NEUTRON	–	CONVEN-TIONAL SIDEWALL	DST
TWIN ARROW NO. 2	PICEANCE	TWINN ARROW	CO	RIO BLANCO	14	T3S	R101W	MESAVERDE COALS	D. INDUCTION D. LATEROLOG M. LATEROLOG SPECTRALOG NEUTRON γ-RAY SONIC DENSITY CALIPER SP	–	CONVEN-TIONAL	–
CONFI-DENTIAL NO. 1	–	–	CO	–	–	–	–	MESAVERDE COALS	D. INDUCTION DENSITY NEUTRON SONIC γ-RAY SP	CUTTINGS GAS ANALYSIS	CONVEN-TIONAL SIDEWALL	DST PRODUC-TION TEST

TABLE 3

Definition of Elastic Constants.[4]

Elastic Constants	Basic Equations	Interrelation of Equations	Equations in Well Logging Terms
Young's Modulus[1)]	$E = \frac{9K\rho V_s^2}{3K + \rho V_s^2}$	$E = \frac{3K\mu}{3K + \mu} = 2\mu(1 + \sigma) = 3K(1 - 2\sigma)$	$E = \left(\frac{\rho}{\Delta t_s^2}\right)\left(\frac{3\Delta t_s^2 - 4\Delta t_c^2}{\Delta t_s^2 - \Delta t_c^2}\right) \times 1.34 \times 10^{10}$
Bulk Modulus[2)]	$K = \rho\left(V_c^2 - \frac{4}{3}V_s^2\right)$	$K = \frac{E\mu}{3(3\mu - E)} = \mu\frac{2(1 + \sigma)}{3(1 - 2\sigma)} = \frac{E}{3(1 - 2\sigma)}$	$K = \rho\left(\frac{3\Delta t_s^2 - 4\Delta t_c^2}{3\Delta t_s^2 \Delta t_c^2}\right) \times 1.34 \times 10^{10}$
Shear Modulus[3)]	$\mu = \rho V_s^2$	$\mu = \frac{3KE}{9K\ E} = 3K\frac{1 - 2\sigma}{2 + 2\sigma} = \frac{E}{2 + 2\sigma}$	$\mu = \left(\frac{\rho}{\Delta t_s^2}\right) \times 1.34 \times 10^{10}$
Poisson's Ratio[4)]	$\sigma = 1/2\ \frac{\left(\frac{V_c^2}{V_s^2}\right) - 2}{\left(\frac{V_c^2}{V_s^2}\right) - 1}$	$\sigma = \frac{3K - 2\mu}{2(3K + \mu)} = \left(\frac{E}{2\mu} - 1\right) = \frac{3K - E}{6K}$	$\sigma = 1/2\left(\frac{\Delta t_s^2 - 2\Delta t_c^2}{\Delta t_s^2 - \Delta t_c^2}\right)$

ρ = bulk density g/cc

V_s = shear velocity, ft/sec

Δt_s = shear travel time, μsec/ft

V_c = comoressional velocity, ft/sec

Δt_c = compressional travel time, μsec/ft

1.34×10^{10} = conversion factor

1) Young's Modulus (E) measures opposition of a substance to extensional stress, $E = \frac{F/A}{\Delta l/l}$

2) Bulk Modulus (K) is the coefficient of incompressibility and measures opposition of a substance to compressional stress, $K = \frac{F/A}{\Delta V/V}$

3) Shear Modulus (μ), also called rigidity modulus, measures the opposition of a substance to shear stresses. Finite values for solids, zero values for fluid, $\mu = \frac{F/A}{\tan S}$

4) Poisson's Ratio (σ) is the ratio of relative decrease in diameter to relative elongation, $\alpha = \frac{\Delta d/d}{\Delta l/l}$

TABLE 4

Gas Desorption Data from the Piceance Basin, Colorado.

WELL	DEPTH OF SAMPLE FT	LITHOLOGY	GAS CONTENT cc/gm	GAS CONTENT ft^3/ton
Twin Arrow #2	685.2-685.6	Coal	4.73	151.4*
Twin Arrow #2	698.1-698.45	Carb. shale/coal	4.1	130.3
Twin Arrow #2	759.2-760.0	Coal	4.88	156.2*
Twin Arrow #2	770.9-771.6	Carb. shale/coal	1.03	33.1
Twin Arrow #2	772.3-772.6	Carb. siltstone	1.7	54.0
Twin Arrow #2	773.3-773.6			
Twin Arrow #2	801.9-802.6	Coal	3.4	107.7
Twin Arrow #2	804.5-805.0	Carb. Shale	4.27	136.6*
Twin Arrow #2	809.3-809.7	Coal	4.6	146.9
Twin Arrow #2	986.5-987.3	Coal	1.43	45.9
Fuelco	1585	Coal	0.56	17.9
Fuelco	1603	Coal	2.5	80.9

* Desorption analysis complete.

TABLE 5

Gas Desorption Data (Confidential Well, Colorado).

DEPTH FT.	LITHOLOGY	GAS CONTENT CONVENTIONAL CORES cc/gm	GAS CONTENT CONVENTIONAL CORES ft^3/ton	GAS CONTENT SIDEWALL CORES cc/gm	GAS CONTENT SIDEWALL CORES ft^3/ton
3652.0-3652.6	Coal	0.2	6.8		
3675.0-3675.8	Coal	7.6	245.2		
3923.0-3924.1	Coal	1.9	62.4		
3937.0-3937.2	Coal	2.8	88.3		
3947.9-3948.2	Coal	2.2	70.4		
4654.0-4655.0	Coal	7.7	246.1		
4655.0-4656.0	Coal	6.8	219.2		
4656.0-4657.0	Coal	8.4	268.8		
4657.0-4658.0	Coal	8.4	268.8		
4658.0-4659.0	Coal	7.3	233.6		
4659.0-4660.0	Coal	9.2	293.7		
4666	Coal			5.6	178.5
4704.6-4705.4	Coal	8.9	285.7		
4705.4-4706.0	Coal	10.6	340.3		
4720	Coal			4.3	136.0
4814	Coal			5.9	189.6
4864	Coal			6.6	209.9
4868	Coal			4.9	157.4
4872	Coal			5.6	178.5
4976	Coal			4.4	142.0
4978	Coal			4.9	157.7
4980	Coal w/shale			4.9	157.7
4982	Very Carbonaceous Shale			2.8	89.9
4984	Coal			4.5	144.0
4986	Coal			4.2	132.8

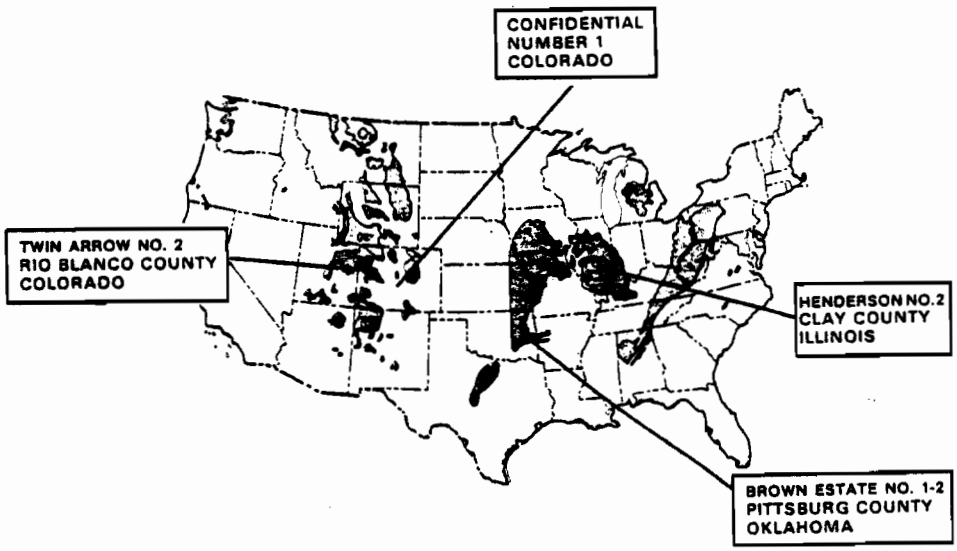

Fig. 1 - Location of bituminous and subbituminous coal fields and the four test wells.

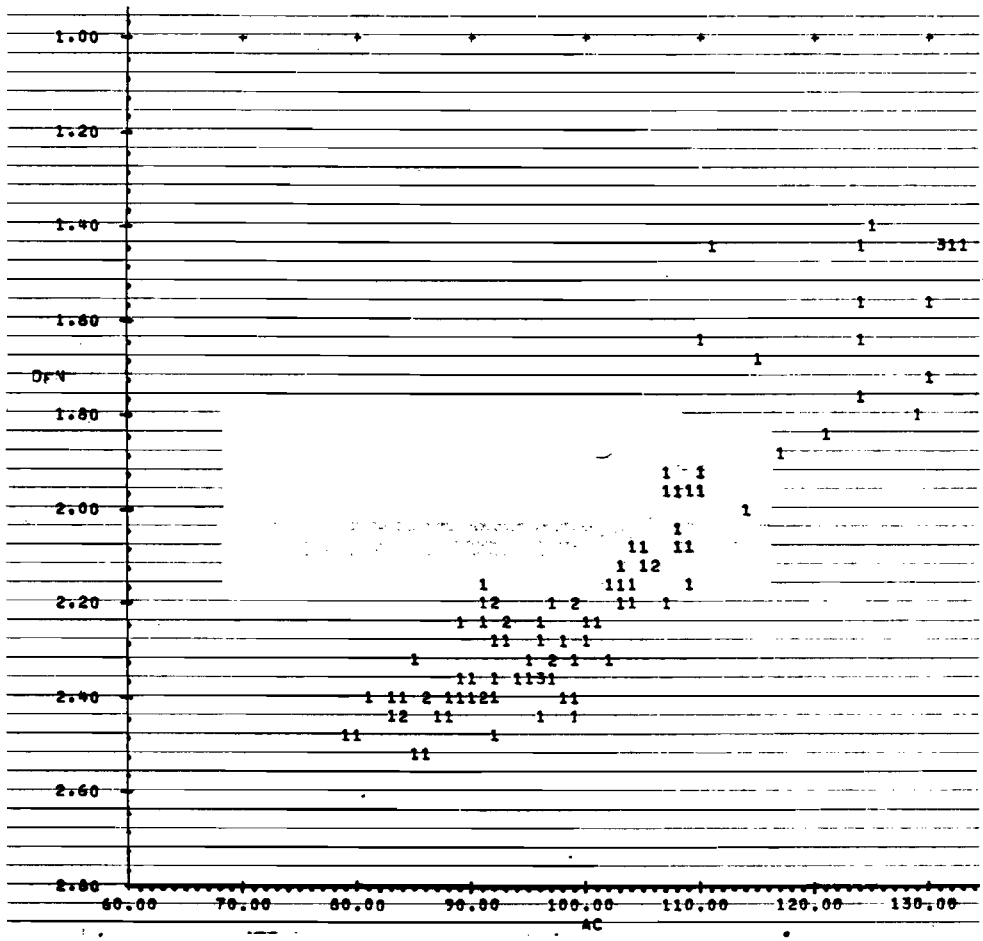

Fig. 2 - Acoustic - Density crossplot over interval at 244 to 259 m (800 to 850 ft) which contains main coal seams (Twin Arrow Well #2).

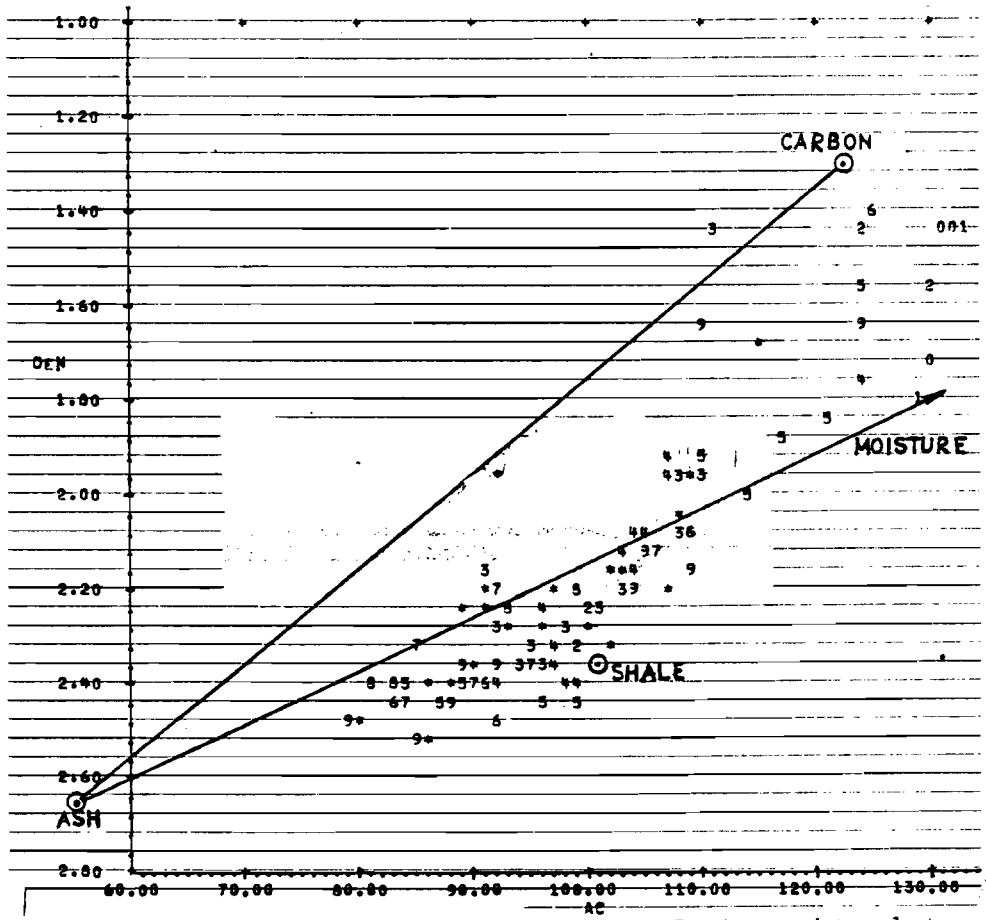

Fig. 3 - Acoustic - density crossplot with gamma ray on Z-axis over interval at 244 to 259 m (800 to 850 ft) which contains main coal seams (Twin Arrow Well #2).

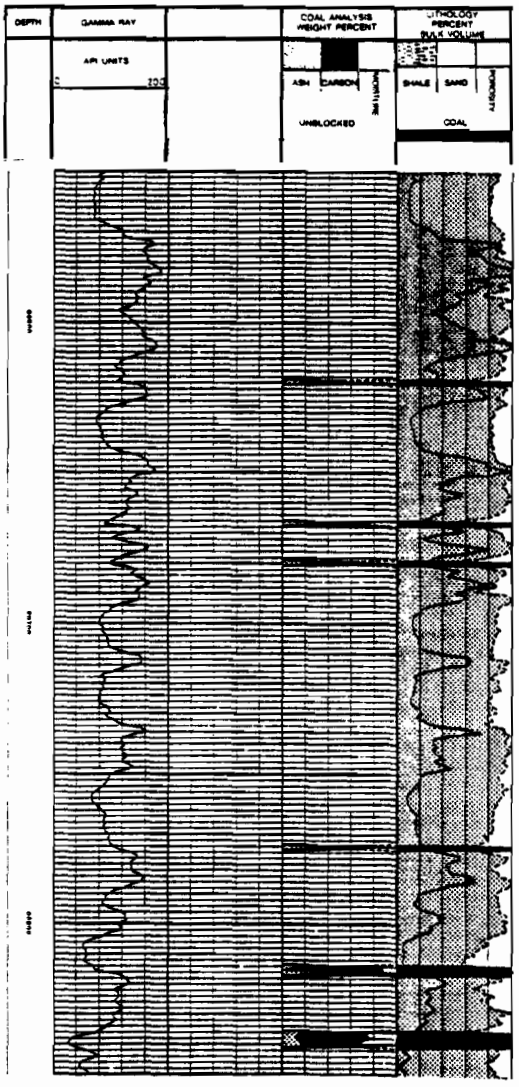

Fig. 6 - Digital epilog^{R} - analysis of coal seams in the Mesaverde formation Piceance Creek Basin, Rio Blanco Co., Colorado (Twin Arrow #2).

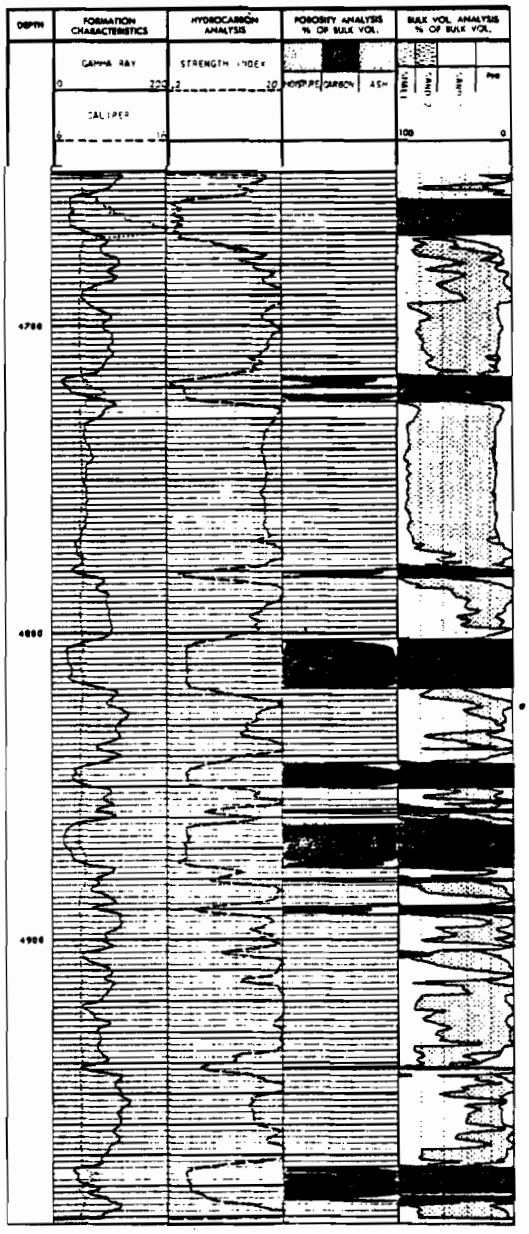

Fig. 7 - Coal log analysis of some of the coal seams in the Mesaverde formation, Colorado (confidential well).

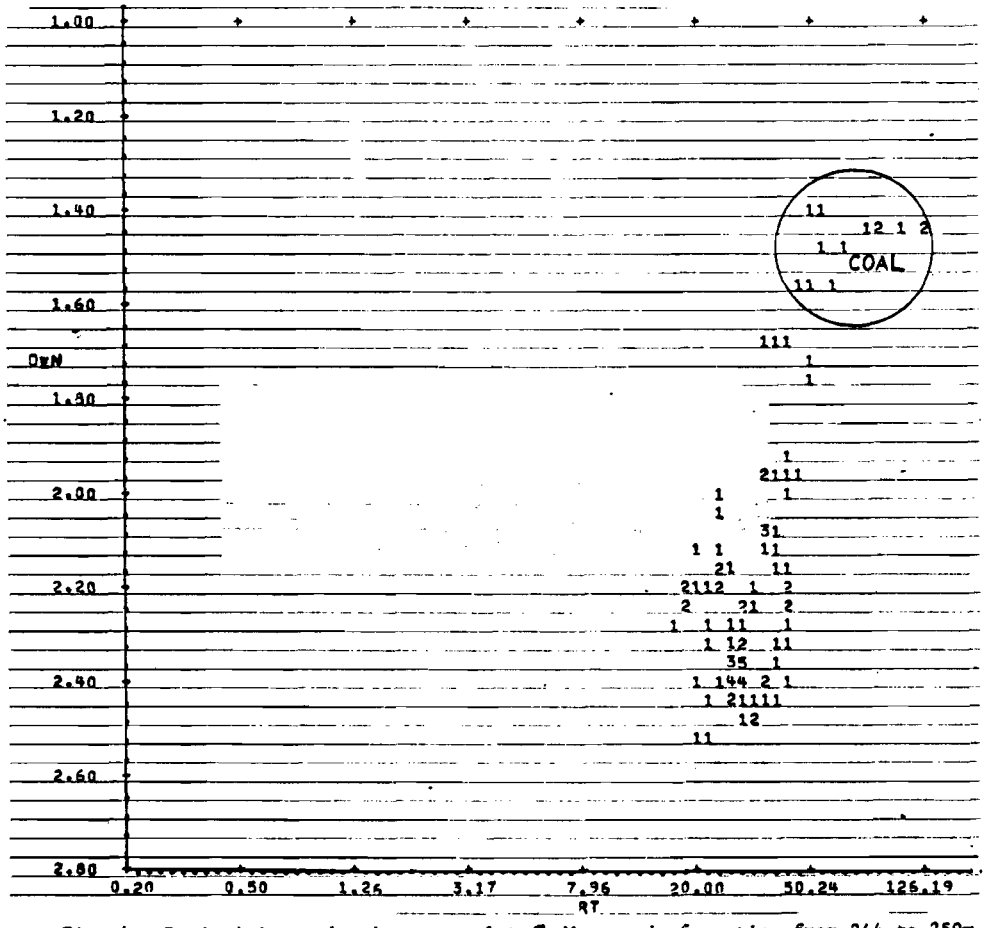

Fig. 4 - Resistivity - density crossplot in Mesaverde formation from 244 to 259m (800 to 850 ft) which contains main coal seams (Twin Arrow Well #2).

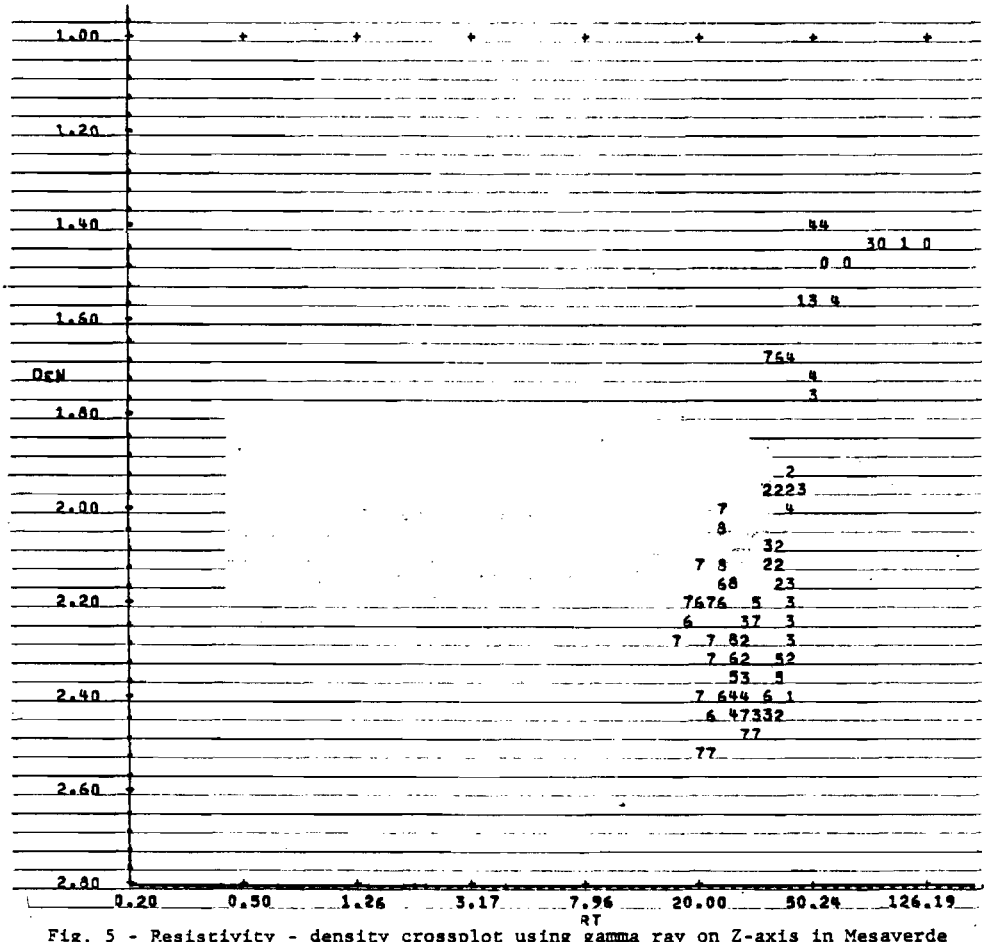

Fig. 5 - Resistivity - density crossplot using gamma ray on Z-axis in Mesaverde formation from 244 to 259 m (800 to 850 ft) which contains main coal seams (Twin Arrow Well # 2).