CHEMICAL ANALYSES OF COAL SAMPLES FROM THE BLACK MESA FIELD, ARIZONA

THE ARIZONA BUREAU OF MINES

GEOLOGICAL SURVEY BRANCH

1977

Circular 18

PRICE FIFTY CENTS

Material contained in this Circular may be quoted or reproduced without special permission provided appropriate acknowledgment is given to the source.

CHEMICAL ANALYSES OF COAL SAMPLES FROM THE BLACK MESA FIELD, ARIZONA

Sample study initiated and coordinated by Richard T. Moore, Principal Geologist, Arizona Bureau of Mines, Tucson, Ariz.; and Vernon E. Swanson, Geologist, U.S. Geological Survey, Denver, Colo.

Samples collected by:
Richard T. Moore and Charles W. Kiven, Geologists, Arizona Bureau of Mines, Tucson, Ariz.

Analytical results compiled by:
Joseph R. Hatch, Geologist, Branch of Coal Resources, U.S. Geological Survey, Denver, Colo.
Scott D. Woodruff, Computer Technician, Branch of Coal Resources, U.S. Geological Survey, Denver, Colo.

Analysts:
Forrest E. Walker, Chemist-in-Charge, U.S. Bureau of Mines, Pittsburgh, Pa.
Claude Huffman, Jr., Chemist-in-Charge, U.S. Geological Survey, Denver, Colo.
J. W. Baker, A. J. Bartel, L. A. Bradley I, G. T. Burrow, E. J. Fennely, J. Gardner, J. C. Hamilton, R. Havens, P. Hemming, J. O. Johnston, R. J. Knight, R. E. McGregor, V. Merritt, H. T. Millard, J. O'Kelley, G. D. Shipley, J. A. Thomas, J. S. Wahlberg, and R. White.

THE ARIZONA BUREAU OF MINES

GEOLOGICAL SURVEY BRANCH

1977

Circular 18

CHEMICAL ANALYSES OF COAL SAMPLES FROM THE BLACK MESA FIELD, ARIZONA

INTRODUCTION

by
Richard T. Moore

Coal mining on a major scale in Arizona began in the early 1970s when Peabody Coal Company started full-scale mining on their Black Mesa leases. These leases cover some 64,800 acres of Navajo and Hopi lands on Black Mesa in northeastern Arizona (see Fig. 1).

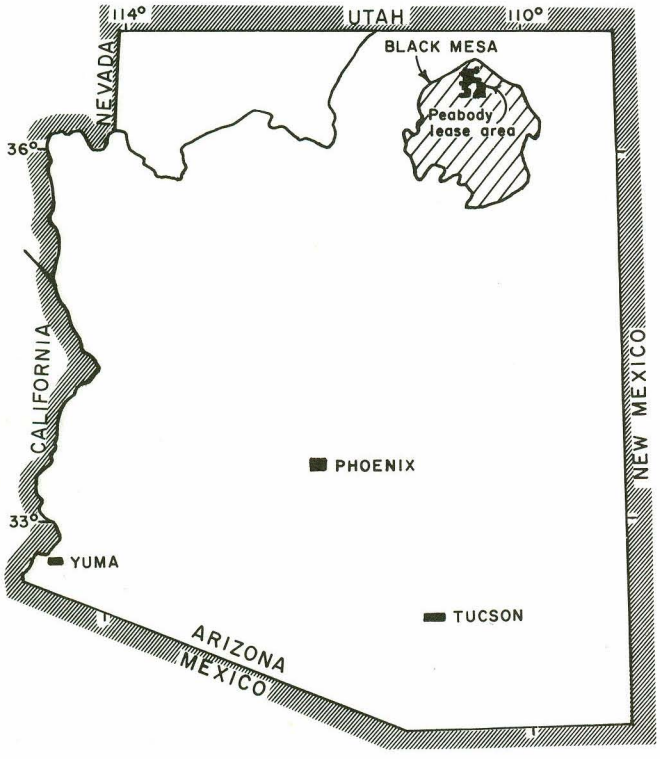


Figure 1. Map showing location of Black Mesa coal field in Arizona.

Currently, Peabody is operating two mines, Black Mesa No. 1 and Black Mesa No. 2 (formerly designated the Kayenta Mine), which supply, respectively, coal to the Mohave electrical generating station in Nevada, near Davis Dam, and the Navajo generating station near Page, Arizona.

The coal being mined comes from three seams, designated the Green, Blue, and Red seams, occurring in the Wepo Formation of Upper Cretaceous age. The following description of the Wepo Formation is abstracted with slight modification from Peirce et al. (1970).

According to available data the Wepo Formation contains not only the highest rank and highest quality coal on Black Mesa but the largest minable reserves as well. The coal seams are thicker, more numerous, more widespread, and more accessible for strip mining. Coal occurs in an alternating sequence of dark olive-gray to brown siltstones and mudstones and yellowish gray sandstones. The Wepo Formation crops out on the northern portion of Black Mesa (Fig. 1). On the extreme northeast it is capped by the massive yellowish gray Yale Point Sandstone. About 1,270 square miles of the Wepo Formation is exposed at the surface of Black Mesa.

The Wepo is 743 feet thick east of Cow Springs and over 600 feet thick in the central part of the mesa. To the north it thins to 318 feet at Rough Rock. Because the top of Black Mesa is an erosion surface the remaining Wepo thickness in a particular area depends upon its structural position and the extent of downcutting by streams. Greater thicknesses of Wepo strata and, therefore, potentially more coal, are preserved in synclines, or downwarps. The Maloney and the Black Mesa synclines are examples of such protective structures. The relatively sharp depositional thinning of Wepo strata to the northeast away from the Maloney synclinal area suggests that a downwarp existed during Wepo deposition. This downwarp and the later movement constituting the Maloney syncline, might well be closely related events. The principal coal reserves that are to be mined by the Peabody Coal Company are, in part at least, associated with the Maloney syncline (Fig. 2).

Because the thickest and most continuous coal beds studied thus far are in the upper half of the Wepo Formation, the best coal prospects appear to be in the northern part of Black Mesa where the upper half of the formation

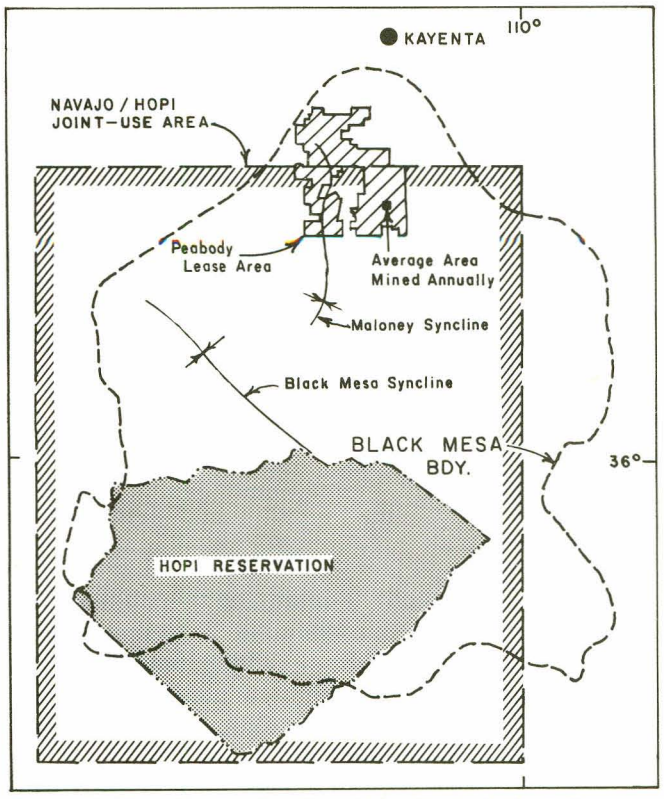


Figure 2. Map showing location of the Peabody Coal Company Black Mesa leases and the Black Mesa and Maloney synclines.

has not been completely eroded away. The Wepo contains at least ten coal beds thicker than three feet in the area examined by Williams (1951, p. 214–5) along the northwest rim. Most of the coal beds occur in the siltstone units below sandstone beds (Repenning and Page, 1956, p. 278). Individual coal seams persist for hundreds of thousands of feet but invariably thin laterally to seams a few inches to a foot thick. However, another seam usually begins within a few feet, vertically. The coal seams average four to eight feet thick although individual seams may be from twelve to twenty feet thick (Kiersch, 1955, p. 51). Because some of the coal near the surface has either been burned out, cut out locally by erosion, or covered, only a detailed drilling program can indicate the presence, thickness, and depth of coal and provide fresh samples for testing. Using such a drilling program, Peabody Coal Company has found sufficient reserves of coal to justify entrance into long-term contractual arrangements as a coal supplier, the first such in Arizona.

Although the two Peabody mines on Black Mesa are managed as separate operations, the mining methods which have been outlined in "Mining Coal on Black Mesa" (Peabody Coal Co., 1970), are essentially the same.

Coal on Black Mesa is close enough to the surface to be removed through surface or strip mining methods, which permit 100 percent recovery of the mineral. At some points the coal seams reach the surface, but in most areas they are covered by shale and rock up to 120 feet deep.

The underground coal seams vary from 4 feet to 30 feet thick. To reach them, the overlying rock and shale, known as overburden, is stripped away by dragline equipment.

In mid-1976 three draglines, one each of 14-yard, 30-yard, and 36-yard capacity, were being used at the Black Mesa No. 1 mine. A single 85-yard unit was in operation at the Black Mesa No. 2 mine. Also, two 90-cubic-yard draglines were under construction, one for each mine.

The coal is then mined and loaded by power shovels into off-highway trucks which can haul up to 120 tons at a time. Fifteen such haulers carry coal from the open mine to the processing centers.

The processing centers consist of truck receiving hoppers, systems of conveyors, and rotary breakers which reduce the coal to two-inch size and remove rock and other extraneous material. The systems also include sampling and weighing facilities. Water spray systems have been installed to avoid coal dust problems where trucks are unloaded and at the stockpile sites.

Power lines have been built to bring in electricity for the processing centers and the mining operations, where the power shovels and draglines are electrically powered. Small plots have been leveled to accommodate transformers, switch houses and oil circuit breakers. This equipment will be moved as mining progresses.

The company has identified 42 separate coal deposits, and mining operations will move to a new deposit as each active deposit is finally depleted.

These deposits lie under a total of nearly 14,000 acres within the 64,858-acre lease area. The coal areas, scattered throughout the lease territory, are the only sections where the surface will be affected. This means that an average of about 400 acres will be mined in any one year.

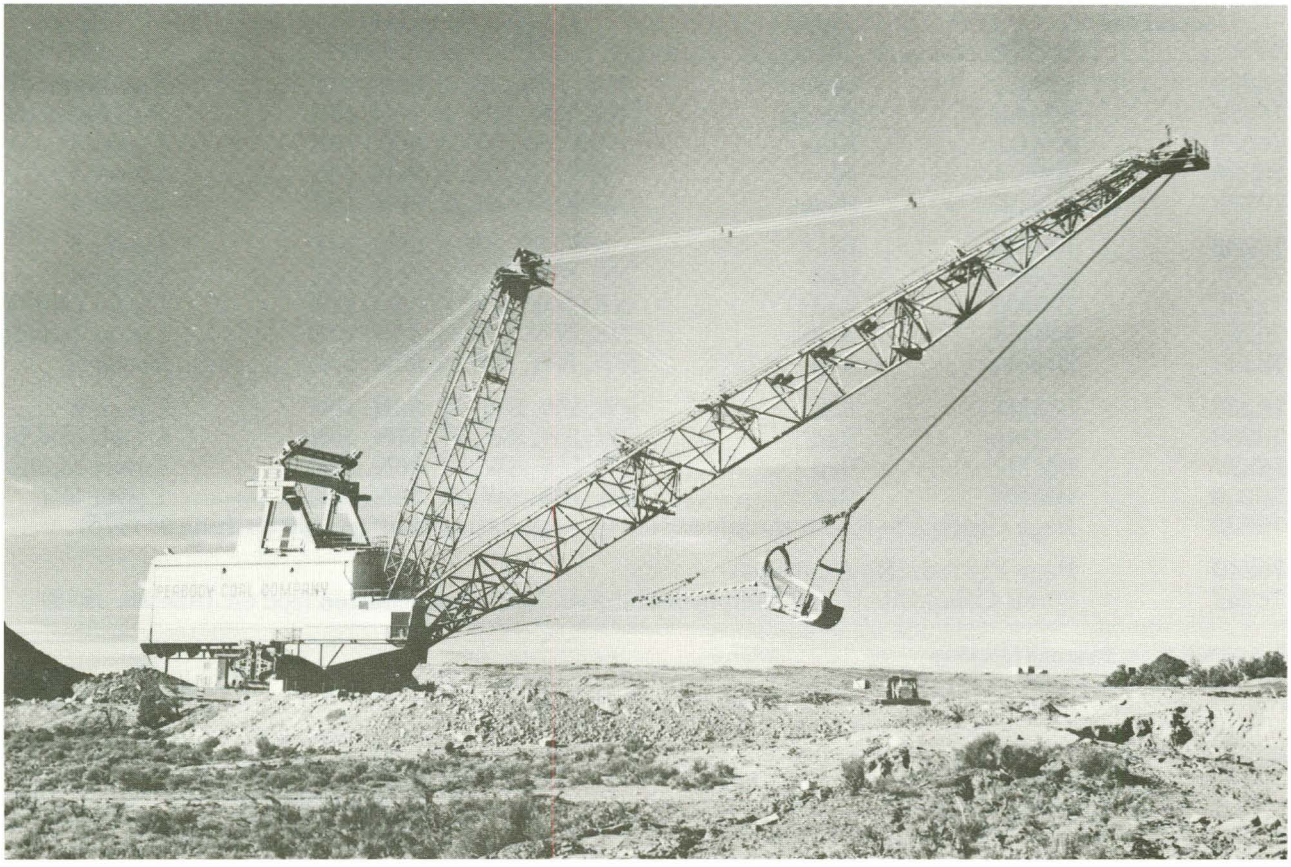
Although current annual production (1976), all of which is shipped to the two generating stations, is estimated to be about 9.8 million tons per year, scheduled production is designed to be at a rate of between 12 and 13 million tons per year. Over the 35-year expected lifespan of the operations, approximately 415 million tons of coal will be produced and converted into electrical energy. The total design generating capacity of the two plants is 3,760 megawatts, of which approximately 1,122 megawatts, or 30 percent, is available to serve customers in Arizona.

To perhaps put this into proper perspective, the combined generating capacity of the two plants is sufficient to meet the normal needs of a city of 3,750,000 people, or more than enough to supply the 2,295,000 people living in Arizona in 1976. Extrapolating from data in the Arizona Statistical Review (1976), the average demand in August, the peak month of 1976, amounted to some 3,600

megawatts and the peak demand probably exceeded 6,000 megawatts.

Arizona's population increased by approximately 29 percent between 1970 and 1976, and if this trend continues at anything like the same rate, it is readily apparent that Arizona's energy requirements will also grow rapidly. In such an event, there is little doubt that Black Mesa coal will become very important to Arizona as a source of this energy.

During field seasons in 1975 and 1976, the Arizona Bureau of Mines, through the support of a grant from the U.S. Geological Survey (Contract #14-08-0001-G-216), collected representative samples of these important coal deposits being mined on Black Mesa and submitted them to the U.S. Geological Survey for analysis. The specific sample locations are recorded in Table 1. Tables 2 through 5 give the results of the analyses.



TABLES OF ANALYSES

by
U.S. Geological Survey
Denver, Colorado 80225

TABLE 1

Sample No. Lab. No.	Field No.	Seam	Location (Protracted) ¼, ¼, ¼, Sec.; Twnshp.; Range*	Sample Interval
D176225	KMA1	Green	NW, NW, SW, 9, 36N, 18E	Full Seam (5′)
D176226	KMA2	Green	NE, SW, NW, 9, 36N, 18E	Full Seam (5′)
D176227	KMB1	Blue	SW, SE, SE, 8, 36N, 18E	Upper 5′
D176228	KMB2	Blue	SW, SE, SE, 8, 36N, 18E	Lower 5′
D176229	KMB3	Blue	NW, SE, SE, 8, 36N, 18E	Upper 5′
D176230	KMB4	Blue	NW, SE, SE, 8, 36N, 18E	Lower 5′
D176231	BMM1	Red	NE, NW, NW, 4, 35N, 18E	Upper 5′
D176232	BMM2	Red	NE, NW, NW, 4, 35N, 18E	Upper Middle 5′
D176233	BMM3	Red	NE, NW, NW, 4, 35N, 18E	Lower Middle 5′
D176234	BMM4	Red	NW, NW, NW, 4, 35N, 18E	Lower 5′
D176235	BMM5	Red	SW, SW, SW, 27, 36N, 18E	Upper 5′
D176236	BMM6	Red	SW, SW, SW, 27, 36N, 18E	Upper Middle 5′
D176237	BMM7	Red	SW, SW, SW, 27, 36N, 18E	Lower Middle 5′
D176238	BMM8	Red	SW, SW, SW, 27, 36N, 18E	Lower 5′
D176239	Page Composite (Grab sample of Navajo Generating Station feed on June 9, 1975)			
D176240	Page Fly Ash (No Analyses)			
D176241	Davis Composite (Grab sample of Mohave Generating Station feed on June 19, 1975)			

*Gila and Salt River Base and Meridian

TABLE 2

Proximate, ultimate, Btu, and forms of sulfur analyses of seven samples from Arizona

[All analyses except Btu are in percent. Original moisture content may be slightly more than shown because samples were collected and transported in plastic bags to avoid metal contamination. Form of analyses: 1, as received; 2, moisture free; 3, moisture and ash free. All analyses by Coal Analysis Section, U.S. Bureau of Mines, Pittsburgh, Pa. Sample D176227* is a composite of samples D176227, D176228, D176229, and D176230; D176231* is a composite of samples D176231, D176232, D176233, and D176234; D176235* is a composite of samples D176235, D176236, D176237, and D176238]

		PROXIMATE ANALYSIS				ULTIMATE ANALYSIS							FORMS OF SULFUR		
Sample	Form of Analysis	Moisture	Volatile Matter	Fixed Carbon	Ash	Hydrogen	Carbon	Nitrogen	Oxygen	Sulfur	Btu	A. D. Loss	Sulfate	Pyritic	Organic
D176225	1	10.6	38.3	42.0	9.1	5.6	61.5	1.2	22.1	0.5	10770	2.3	0.01	0.04	0.49
	2	—	42.9	46.9	10.2	4.9	68.8	1.4	14.1	.6	12050	—	.01	.04	.55
	3	—	47.8	52.2	—	5.5	76.7	1.5	15.6	.7	13430	—	.01	.05	.61
D176226	1	9.3	40.8	41.4	8.5	5.7	63.5	1.1	20.7	.5	11100	1.8	.02	.07	.41
	2	—	44.9	45.8	9.3	5.1	70.0	1.2	13.8	.6	12240	—	.02	.08	.45
	3	—	49.6	50.4	—	5.6	77.2	1.4	15.2	.6	13500	—	.02	.08	.50
D176227*	1	9.3	40.1	45.3	5.3	5.7	66.1	1.2	21.3	.4	11560	1.7	.01	.01	.36
	2	—	44.2	50.0	5.8	5.1	72.9	1.3	15.4	.4	12750	—	.01	.01	.40
	3	—	47.0	53.0	—	5.4	77.4	1.4	15.3	.4	13530	—	.01	.01	.43
D176231*	1	10.2	41.2	43.9	4.7	5.9	65.6	1.1	22.4	.3	11470	2.5	.02	.02	.30
	2	—	45.8	49.0	5.2	5.3	73.0	1.2	14.9	.4	12760	—	.02	.02	.34
	3	—	48.4	51.6	—	5.6	77.0	1.3	15.7	.4	13470	—	.02	.02	.35
D176235*	1	8.6	40.0	42.3	9.1	5.4	63.2	1.1	20.7	.5	10910	1.7	.03	.05	.37
	2	—	43.8	46.3	9.9	4.9	69.2	1.2	14.3	.5	11940	—	.03	.05	.41
	3	—	48.6	51.4	—	5.4	76.8	1.3	16.0	.5	13250	—	.04	.06	.45
D176239	1	10.9	37.5	44.5	7.1	5.7	63.1	1.1	22.6	.4	10930	2.5	.02	.02	.39
	2	—	42.0	50.0	8.0	5.0	70.9	1.3	14.3	.5	12270	—	.02	.02	.44
	3	—	45.7	54.3	—	5.4	77.0	1.4	15.7	.5	13330	—	.02	.02	.47
D176241	1	21.9	31.4	39.6	7.1	6.3	54.5	.9	30.9	.3	9490	15.7	.10	.02	.17
	2	—	40.2	50.6	9.2	4.9	69.8	1.2	14.5	.4	12160	—	.13	.02	.21
	3	—	44.2	55.8	—	5.4	76.8	1.3	16.1	.4	13380	—	.14	.02	.23

TABLE 3

Major and minor oxide and trace-element composition of the laboratory ash of 16 coal samples from Black Mesa Field, Ariz.

[Values are in either percent or parts per million. The coals were ashed at 525°C. L after a value means less than the value shown, N means not detected, and B means not determined. S after the element title means that the values listed were determined by semiquantitative spectrographic analysis. The spectrographic results are to be identified with geometric brackets whose boundaries are 1.2, 0,83, 0.56, 0.38, 0.26, 0.18, 0.12, etc., but are reported arbitrarily as mid-points of those brackets, 1.0, 0.7, 0.5, 0.3, 0.2, 0.15, 0.1, etc. The precision of the spectrographic data is approximately one bracket at 68-percent, or two brackets at 95-percent confidence]

Sample	Ash %	SiO_2 %	Al_2O_3 %	CaO %	MgO %	Na_2O %	K_2O %	Fe_2O_3 %	MnO %	TiO_2 %
D176225	12.5	55.	22.	4.0	1.29	1.46	1.3	5.6	0.015	1.0
D176226	10.8	45.	16.	12.	2.21	.70	.92	5.6	.016	.84
D176227	6.0	43.	17.	10.	1.73	3.37	.47	5.9	.017	1.2
D176228	3.5	24.	16.	14.	2.16	4.79	.32	10.	.018	1.0
D176229	9.3	47.	19.	8.8	1.34	2.40	.50	4.0	.012	1.3
D176230	4.4	28.	17.	14.	2.37	4.09	.36	8.8	.015	1.2
D176231	4.9	31.	13.	19.	4.17	.86	.60	8.0	.035	.93
D176232	5.9	23.	8.5	27.	2.89	1.19	.20	6.7	.028	.81
D176233	5.0	29.	13.	16.	3.47	1.89	.27	9.8	.028	.86
D176234	5.5	24.	10.	25.	2.52	2.23	.28	6.4	.017	.78
D176235	12.3	49.	15.	13.	1.33	:45	.86	4.5	.008	.98
D176236	7.4	27.	9.3	25.	3.07	.80	.28	5.7	.010	.85
D176237	10.0	59.	12.	7.7	2.29	.39	.98	4.6	.009	1.1
D176238	7.5	37.	16.	15.	2.54	.45	.52	5.6	.014	.97
D176239	7.9	46.	18.	9.0	1.98	2.12	.80	6.0	.015	.98
D176241	9.2	45.	13.	13.	2.16	1.19	.76	5.7	.023	.97

Sample	P_2O_5 %	SO_3 %	Cl %	Cd PPM	Cu PPM	Li PPM	Pb PPM	Zn PPM	Ag PPM-S	B PPM-S
D176225	1.0 L	6.0	0.20 L	1.0 L	58.	67.	25. L	69.	N	300
D176226	1.0 L	8.5	.20 L	1.0 L	62.	37.	25. L	40.	N	300
D176227	1.0 L	14.	.20 L	1.0 L	127.	50.	25.	23.	N	1000
D176228	1.0 L	23.	.20 L	1.0 L	89.	50.	30.	32.	N	1500
D176229	1.0 L	8.9	.20 L	1.0 L	90.	51.	40.	23.	N	300
D176230	1.0 L	19.	.20 L	1.0 L	87.	46.	40.	25.	N	1000
D176231	1.0 L	16.	.20 L	1.0 L	71.	29.	30.	136.	N	300
D176232	1.0 L	12.	.20 L	1.0 L	57.	20.	30.	60.	N	300
D176233	1.0 L	16.	.20 L	1.0 L	88.	38.	45.	107.	N	300
D176234	1.0 L	15.	.20 L	1.0 L	61.	28.	25.	118.	N	500
D176235	1.0 L	7.3	.20 L	1.0 L	60.	45.	25.	66.	N	200
D176236	1.0 L	11.	.20 L	1.0 L	60.	42.	40.	48.	N	300
D176237	1.0 L	8.4	.20 L	1.5	65.	39.	20.	150.	N	300
D176238	1.0 L	14.	.20 L	1.0 L	68.	72.	75.	42.	N	300
D176239	1.0 L	13.	.20 L	1.0 L	68.	44.	30.	81.	1	500
D176241	1.0 L	11.	.20 L	1.0 L	69.	36.	20.	102.	N	300

TABLE 3 (Continued)

Major and minor oxide and trace-element composition of the laboratory ash of 16 coal samples from Black Mesa Field, Ariz.

Sample	Ba PPM-S	Be PPM-S	Ce PPM-S	Co PPM-S	Cr PPM-S	Ga PPM-S	La PPM-S	Mo PPM-S	Nb PPM-S	Nd PPM-S
D176225	3000	7	500 L	15	70	30	100 L	15	20	150 L
D176226	3000	3	500 L	10	30	30	100 L	10	20 L	N
D176227	5000	7	500 L	15	30	30	100 L	15	20	N
D176228	5000	5	500 L	15	70	30	100 L	10	20	N
D176229	3000	7	500 L	15	30	50	100	15	20	150 L
D176230	10000	10	500 L	15	50	30	100 L	30	30	N
D176231	5000	N	500 L	15	50	30	100 L	7	20	N
D176232	5000	N	N	10	30	30	N	N	20	B
D176233	5000	7	500 L	20	30	30	150	30	20	150 L
D176234	7000	3	N	15	50	30	100 L	15	20	N
D176235	2000	3	N	15	30	30	100 L	10	20	N
D176236	7000	N	500 L	10 L	30	20	100 L	7	20	N
D176237	5000	15	500 L	30	70	30	100	7	30	150 L
D176238	3000	7	500 L	10	50	30	100 L	20	20	N
D176239	5000	7	500 L	15	50	30	100 L	7	20	N
D176241	3000	5	N	15	50	30	N	7	20	B

Sample	Ni PPM-S	Sc PPM-S	Sn PPM-S	Sr PPM-S	V PPM-S	Y PPM-S	Yb PPM-S	Zr PPM-S
D176225	30	20	N	2000	150	30	3	200
D176226	30	15	N	700	70	50	3	200
D176227	30	15	70	2000	70	50	5	300
D176228	50	15	70	3000	100	50	5	200
D176229	20	20	N	1000	150	50	5	300
D176230	30	20	N	2000	100	70	7	150
D176231	30	15	N	1000	100	50	3	200
D176232	30	15	N	2000	70	20	2	150
D176233	70	20	N	1500	150	70	7	150
D176234	50	15	N	3000	100	30	3	150
D176235	50	15	N	700	70	50	3	300
D176236	30	15	N	2000	70	30	3	200
D176237	50	20	N	1000	70	100	10	300
D176238	30	15	N	700	100	50	3	150
D176239	30	15	N	700	100	50	5	200
D176241	50	15	N	700	150	50	5	200

TABLE 4

Major, minor, and trace-element composition of 16 coal samples from Black Mesa Field, Ariz., reported on whole-coal basis

[Values are in either percent or parts per million. Si, Al, Ca, Mg, Na, K, Fe, Mn, Ti, P, Cl, Cd, Cu, Li, Pb, and Zn values were calculated from analysis of ash. As, F, Hg, Sb, Se, Th, and U values are from direct determinations on air-dried (32°C) coal. The remaining analyses were calculated from spectrographic determinations on ash. L after a value means less than the value shown, N means not detected, and B means not determined]

Sample	Si %	Al %	Ca %	Mg %	Na %	K %	Fe %	Mn PPM	Ti %	P PPM
D176225	3.2	1.4	0.36	0.098	0.135	0.13	0.49	15.	0.078	550. L
D176226	2.3	.94	.93	.144	.056	.082	.43	13.	.055	470. L
D176227	1.2	.54	.43	.062	.150	.023	.25	8.1	.043	260. L
D176228	.39	.29	.35	.046	.124	.009	.25	4.9	.021	150. L
D176229	2.1	.94	.58	.075	.166	.039	.26	8.8	.072	410. L
D176230	.58	.39	.44	.063	.133	.013	.27	5.1	.032	190. L
D176231	.70	.34	.66	.123	.031	.024	.27	13.	.027	210. L
D176232	.62	.27	1.1	.103	.052	.010	.28	13.	.029	260. L
D176233	.69	.34	.57	.105	.070	.011	.34	11.	.026	220. L
D176234	.61	.29	.98	.084	.091	.013	.25	7.2	.026	240. L
D176235	2.8	.99	1.1	.098	.041	.089	.38	7.4	.072	540. L
D176236	.92	.36	1.3	.137	.044	.017	.30	5.9	.038	320. L
D176237	2.8	.65	.55	.138	.029	.081	.32	7.0	.066	440. L
D176238	1.3	.64	.80	.115	.025	.033	.29	7.9	.044	330. L
D176239	1.7	.76	.51	.094	.124	.052	.33	9.1	.046	340. L
D176241	1.9	.61	.85	.120	.081	.058	.37	17.	.053	400. L

Sample	Cl %	As PPM	Cd PPM	Cu PPM	F PPM	Hg PPM	Li PPM	Pb PPM	Sb PPM	Se PPM
D176225	0.025 L	10.	0.1 L	7.3	50.	0.05	8.4	3.1 L	0.4	1.2
D176226	.022 L	1.	.1 L	6.7	35.	.05	4.0	2.7 L	.4	1.3
D176227	.012 L	1.	.1 L	7.6	50.	.03	3.0	1.5	.5	1.9
D176228	.007 L	1. L	.04 L	3.1	30.	.03	1.8	1.1	.2	1.4
D176229	.019 L	2.	.1 L	8.4	50.	.02	4.7	3.7	.3	2.1
D176230	.009 L	1.	.04 L	3.8	20. L	.02	2.0	1.8	.2	1.6
D176231	.010 L	1.	.05 L	3.5	20. L	.03	1.4	1.5	.1	1.5
D176232	.012 L	1. L	.1 L	3.4	25.	.02	1.2	1.8	.2	1.1
D176233	.010 L	1.	.05 L	4.4	20. L	.02	1.9	2.3	.4	2.1
D176234	.011 L	1.	.1 L	3.4	25.	.02	1.5	1.4	.2	1.6
D176235	.025 L	3.	.1 L	7.4	35.	.07	5.5	3.1	.6	1.9
D176236	.015 L	2.	.1 L	4.4	30.	.02	3.1	3.0	.1	1.4
D176237	.020 L	2.	.2	6.5	75.	.03	3.9	2.0	.1	1.8
D176238	.015 L	1.	.1 L	5.1	30.	.03	5.4	5.6	.4	1.5
D176239	.016 L	2.	.1 L	5.4	40.	.03	3.5	2.4	.2	1.5
D176241	.018 L	1.	.1 L	6.3	25.	.03	3.3	1.8	.3	1.5

TABLE 4 (Continued)

Major, minor, and trace-element composition of 16 coal samples from Black Mesa Field, Ariz., reported on whole-coal basis

Sample	Th PPM	U PPM	Zn PPM	Ag PPM-S	B PPM-S	Ba PPM-S	Be PPM-S	Ce PPM-S	Co PPM-S	Cr PPM-S
D176225	3.0 L	1.1	8.6	N	30	300	1	70 L	2	10
D176226	3.7	.6	4.3	N	30	300	.3	50 L	1	3
D176227	3.0 L	.2 L	1.4	N	70	300	.5	30 L	1	1.5
D176228	3.0 L	.2 L	1.1	N	50	150	.15	15 L	.5	2
D176229	3.0 L	1.0	2.1	N	30	300	.7	50 L	1.5	3
D176230	3.0 L	.2 L	1.1	N	50	500	.5	20 L	.7	2
D176231	3.0 L	.2 L	6.7	N	15	200	N	20 L	.7	2
D176232	3.0 L	.2 L	3.5	N	15	300	N	N	.7	1.5
D176233	3.0 L	.2 L	5.3	N	15	200	.3	20 L	1	1.5
D176234	3.0 L	.2 L	6.5	N	30	500	.15	N	.7	3
D176235	3.0 L	.9	8.1	N	20	200	.3	N	2	3
D176236	3.0 L	.5	3.6	N	20	500	N	30 L	.7 L	2
D176237	3.0 L	1.1	15.0	N	30	500	1.5	50 L	3	7
D176238	3.0 L	.6	3.2	N	20	200	.5	30 L	.7	3
D176239	3.0 L	.8	6.4	.07	50	500	.5	50 L	1	5
D176241	3.0 L	.5	9.4	N	30	300	.5	N	1.5	5

Sample	Ga PPM-S	La PPM-S	Mo PPM-S	Nb PPM-S	Nd PPM-S	Ni PPM-S	Sc PPM-S	Sn PPM-S	Sr PPM-S	V PPM-S
D176225	3	15 L	2	2	20 L	3	2	N	200	20
D176226	3	10 L	1	2 L	N	3	1.5	N	70	7
D176227	1.5	7 L	1	1	N	1.5	1	5	100	5
D176228	1	3 L	.3	.7	N	1.5	.5	2	100	3
D176229	5	10	1.5	2	15 L	2	2	N	100	15
D176230	1.5	5 L	1.5	1.5	N	1.5	1	N	100	5
D176231	1.5	5 L	.3	1	N	1.5	.7	N	50	5
D176232	1.5	N	N	1	B	1.5	1	N	100	5
D176233	1.5	7	1.5	1	7 L	3	1	N	70	7
D176234	1.5	5 L	.7	1	N	3	.7	N	150	5
D176235	3	15 L	1.5	2	N	7	2	N	100	10
D176236	1.5	7 L	.5	1.5	N	2	1	N	150	5
D176237	3	10	.7	3	15 L	5	2	N	100	7
D176238	2	7 L	1.5	1.5	N	2	1	N	50	7
D176239	2	7 L	.5	1.5	N	2	1	N	50	7
D176241	3	N	.7	2	B	5	1.5	N	70	15

Sample	Y PPM-S	Yb PPM-S	Zr PPM-S
D176225	3	0.3	20
D176226	5	.3	20
D176227	3	.3	15
D176228	1.5	.15	7
D176229	5	.5	30
D176230	3	.3	7
D176231	2	.15	10
D176232	1	.1	10
D176233	3	.3	7
D176234	1.5	.15	7
D176235	7	.3	30
D176236	2	.2	15
D176237	10	1	30
D176238	3	.2	10
D176239	5	.5	15
D176241	5	.5	20

TABLE 5

Content of seven trace elements in 16 coal samples from Black Mesa Field, Ariz.

[Analyses on air-dried (32°C) coal. All values are in parts per million. L after a value means less than the value shown]

Sample	As PPM	F PPM	Hg PPM	Sb PPM	Se PPM	Th PPM	U PPM
D176225	10.	50.	0.05	0.4	1.2	3.0 L	1.1
D176226	1.	35.	.05	.4	1.3	3.7	.6
D176227	1.	50.	.03	.5	1.9	3.0 L	.2 L
D176228	1. L	30.	.03	.2	1.4	3.0 L	.2 L
D176229	2.	50.	.02	.3	2.1	3.0 L	1.0
D176230	1.	20. L	.02	.2	1.6	3.0 L	.2 L
D176231	1.	20. L	.03	.1	1.5	3.0 L	.2 L
D176232	1. L	25.	.02	.2	1.1	3.0 L	.2 L
D176233	1.	20. L	.02	.4	2.1	3.0 L	.2 L
D176234	1.	25.	.02	.2	1.6	3.0 L	.2 L
D176235	3.	35.	.07	.6	1.9	3.0 L	.9
D176236	2.	30.	.02	.1	1.4	3.0 L	.5
D176237	2.	75.	.03	.1	1.8	3.0 L	1.1
D176238	1.	30.	.03	.4	1.5	3.0 L	.6
D176239	2.	40.	.03	.2	1.5	3.0 L	.8
D176241	1.	25.	.03	.3	1.5	3.0 L	.5

Tables 6 and 7 show comparative data on the content of various elements and oxides for Black Mesa and Rocky Mountain province coals. In these tables the geometric mean (GM) is used as the estimate of the most probable concentration (mode); the geometric mean is the antilog of the logarithms of concentrations. The measure of scatter about the mode used here is the geometric deviation (GD) which is the antilog of the standard deviation of the logarithms of concentration. These statistics are used because of the common tendency for the amounts of trace elements in natural materials to exhibit positively skewed frequency distributions; these distributions are normalized by analyzing and summarizing trace element data on a logarithmic basis.

If the frequency distributions are, in fact, log-normal, the geometric mean is the best estimate of the mode, and the estimated range of the central two-thirds of the observed distribution has a lower limit equal to GM/GD and an upper limit equal to GM·GD. The estimated range of the central 95 percent of the observed distribution has a lower limit equal to $GM/(GD)^2$ and an upper limit equal to $GM\cdot(GD)^2$ (Connor and others, 1976).

Although the geometric mean is, in general, an adequate estimate of the most common concentration, it is, nevertheless, a biased estimate of the arithmetic mean. In the summary tables of data, the estimates of the arithmetic means are Sichel's *t* statistic (Miesch, 1967). In this report the terms arithmetic mean, average value, and abundance are used synonymously.

A common problem in statistical summaries of trace element data arises when the element concentration in one or more of the samples lies below the limit of analytical detection, resulting in a censored distribution. Procedures developed by Cohen (1959) were used here to compute unbiased estimates of the geometric mean, geometric deviation, and arithmetic mean where the concentration data are censored.

TABLE 6a

Arithmetic mean, observed range, geometric mean, and geometric deviation of 15 major and minor oxides and trace elements in the ash of 26 Black Mesa field coal samples

[All samples were ashed at 525°C; L after a value means less than the value shown]

Oxide or element	Arithmetic mean (abundance)	Observed range Minimum	Observed range Maximum	Geometric mean (expected value)	Geometric deviation
Ash %	8.0	3.2	13.6	7.4	1.5
SiO_2 %	38	19	59	36	1.4
Al_2O_3 %	15	5.9	28	15	1.4
CaO %	15	3.4	27	13	1.7
MgO %	2.42	.75	6.11	2.20	1.5
Na_2O %	1.9	.39	4.79	1.45	2.1
K_2O %	.49	.1 L	1.3	.38	2.1
Fe_2O %	6.1	2.1	10	6.2	1.3
MnO %	.018	.008	.035	.016	1.5
TiO_2 %	1.0	.78	1.3	.98	1.2
SO_3 %	13	6.0	23	12	1.4
Cd ppm	1 L	1 L	2.0	1 L	3.0
Cu ppm	70	54	127	69	1.2
Li ppm	47	20	89	44	1.4
Pb ppm	31	20 L	75	29	1.5
Zn ppm	67	20	275	54	1.9

TABLE 6b

Arithmetic mean, observed range, geometric mean, and geometric deviation of 15 major and minor oxides and trace elements in the ash of 295 Rocky Mountain province coal samples

[All samples were ashed at 525°C; L after a value means less than the value shown]

Oxide or element	Arithmetic mean (abundance)	Observed range Minimum	Observed range Maximum	Geometric mean (expected value)	Geometric deviation
Ash %	13.3	1.76	88.2	10.9	1.9
SiO_2 %	46	15	79	44	1.4
Al_2O_3 %	21	4.3	35	19	1.4
CaO %	8.9	.21	35	6.2	2.4
MgO %	1.63	.22	7.10	1.4	1.8
Na_2O %	1.39	.08	8.56	.68	3.3
K_2O %	.65	.05	3.0	.45	2.3
Fe_2O_3 %	7.6	1.1	26	4.5	2.8
MnO %	.049	.004	.55	.029	2.8
TiO_2 %	.89	.02 L	1.8	.81	1.6
SO_3 %	8.4	.10 L	29	5.1	2.7
Cd ppm	.7	.5 L	4.0	.6	1.9
Cu ppm	87	22	1,260	77	1.6
Li ppm	88	10 L	328	73	1.9
Pb ppm	45	20 L	195	41	1.5
Zn ppm	77	13	1,820	62	1.9

TABLE 7a

Arithmetic mean, observed range, geometric mean, and geometric deviation of 36 elements in 26 Black Mesa coal samples (whole-coal basis). For comparison, average shale values are listed (Turekian and Wedepohl, 1961)

[As, F, Hg, Sb, Se, Th, and U values used to calculate the statistics were determined directly on whole coal. All other values used were calculated from determinations made on coal ash. L means less than the value shown]

Element	Arithmetic mean (abundance)	Observed range Minimum	Observed range Maximum	Geometric mean (expected value)	Geometric deviation	Average shale
Si %	1.6	0.28	3.3	1.2	2.0	7.3
Al %	.69	.21	1.8	.57	1.8	8.0
Ca %	.78	.28	1.3	.70	1.6	2.21
Mg %	.104	.046	.245	.098	1.4	1.55
Na %	.093	.025	.166	.079	1.8	.96
K %	.037	.004	.13	.024	2.5	2.66
Fe %	.31	.18	.53	.31	1.2	4.72
Mn ppm	9.7	4.9	16	9.0	1.5	850
Ti %	.046	.021	.078	.042	1.5	.46
As ppm	2	1 L	10	1	1.9	13
Cd ppm	.1 L	.03L	.23	1 L	1.4	.3
Cu ppm	5.5	2.3	11.7	5.1	1.5	45
F ppm	51	20 L	100	41	1.9	740
Hg ppm	.04	.02	.08	.03	1.6	.4
Li ppm	3.9	1.2	10.5	3.2	1.8	66
Pb ppm	2.7	1.0	5.6	2.4	1.7	20
Sb ppm	.3	.1	.6	.2	1.7	1.5
Se ppm	1.6	.7	3.1	1.5	1.4	.6
Th ppm	2.2	2.1	4.6	2.0	1.6	12
U ppm	.6	.2 L	1.1	.4	2.7	3.7
Zn ppm	5.6	1.1	32.5	4.0	2.3	95
B ppm	20	15	70	20	1.6	100
Ba ppm	300	150	500	300	1.5	580
Be ppm	.5	.15L	1.5	.3	2.5	3
Co ppm	1.5	.5	7	1	1.9	19
Cr ppm	3	1	10	3	1.7	90
Ga ppm	2	.7	7	2	1.8	19
Mo ppm	1	.3 L	2	.7	1.8	2.6
Nb ppm	1.5	.7	3	1	2.0	11
Ni ppm	2	.7	10	2	1.9	68
Sc ppm	1.5	.5	2	1	1.5	13
Sr ppm	150	30	500	100	1.9	300
V ppm	7	3	20	7	1.6	130
Y ppm	3	1	10	3	1.8	26
Yb ppm	.3	.1	1	.3	1.7	2.6
Zr ppm	15	3	70	15	1.9	160

TABLE 7b

Arithmetic mean, observed range, geometric mean, and geometric deviation of 36 elements in 295 Rocky Mountain province coal samples (whole-coal basis). For comparison, average shale values are listed (Turekian and Wedepohl, 1961)

[As, F, Hg, Sb, Se, Th, and U values used to calculate the statistics were determined directly on whole coal. All other values used were calculated from determinations made on coal ash. L means less than the value shown]

Element	Arithmetic mean (abundance)	Observed range Minimum	Observed range Maximum	Geometric mean (expected value)	Geometric deviation	Average shale
Si %	3.2	0.9	23	2.3	2.3	7.3
Al %	1.6	.14	13	1.1	2.3	8.0
Ca %	.61	.05	3.7	.48	2.0	2.21
Mg %	.107	.015	.76	.089	1.8	1.55
Na %	.155	.002	.76	.055	4.2	.96
K %	.092	.003	1.7	.041	3.6	2.66
Fe %	.64	.10	4.2	.34	3.1	4.72
Mn ppm	33	2.7	492	20	2.6	850
Ti %	.062	.001 L	.54	.047	2.1	.46
As ppm	2	1 L	50	2	2.5	13
Cd ppm	.08	.021	.50	.05	2.7	.3
Cu ppm	10.8	1.3	100	8.4	2.0	45
F ppm	95	20 L	920	69	2.2	740
Hg ppm	.08	.01	1.48	.05	2.4	.4
Li ppm	13	.44 L	82.9	8.0	2.7	66
Pb ppm	6.5	.95	62	4.7	2.2	20
Sb ppm	.4	.05 L	5.2	.3	2.2	1.5
Se ppm	1.6	.10 L	5.7	1.2	2.1	.6
Th ppm	4.2	1.7	34.8	2.9	2.5	12
U ppm	1.9	.1	23.8	1.1	2.8	3.7
Zn ppm	10.7	1.0	380	6.8	2.6	95
B ppm	70	7	300	70	2.2	100
Ba ppm	300	3	1,500	150	2.6	580
Be ppm	.7	.05	3	.5	2.3	3
Co ppm	2	.3	10	1.5	2.0	19
Cr ppm	5	.5	70	5	2.2	90
Ga ppm	5	.3	30	3	2.3	19
Mo ppm	2	.2	15	1.5	2.3	2.6
Nb ppm	1	.3	30	.5	2.6	11
Ni ppm	3	.7	20	2	2.1	68
Sc ppm	2	.3	15	1.5	2.0	13
Sr ppm	100	5	700	100	2.1	300
V ppm	15	1.5	100	100	2.1	130
Y ppm	7	.5	30	5	2.1	26
Yb ppm	.7	.03	3	.5	2.2	2.6
Zr ppm	30	3	100	20	2.3	160

REFERENCES CITED

Cohen, A.C., 1959, Simplified estimators for the normal distribution when samples are singly censored or truncated: Technometrics, v. 1, no. 3, p. 217–237.

Connor, J. J., Keith, J. R., and Anderson, B. M., 1976, Trace-metal variation in soils and sagebrush in the Powder River Basin, Wyoming and Montana: U.S. Geol. Survey, Jour. Research, v. 4, no. 1, p. 49–59.

Kiersch, G. A., 1955, Metalliferous minerals and mineral fuels—geology, evaluation, and uses, and a section on general geology, v. 1, *in* Mineral resources, Navajo-Hopi Indian Reservations, Arizona-Utah: The Univ. Arizona Press (Tucson), 75 p.

Miesch, A. T., 1967, Methods of computation for estimating geochemical abundances: U.S. Geol. Survey, Prof. Paper 574-B, 15 p.

Peabody Coal Co., 1970, Mining coal on Black Mesa: Peabody Coal Co. (St. Louis, MO), 12 p.

Peirce, H. Wesley, and Wilt, Jan Carol, 1970, Coal, *in* Coal, oil, natural gas, helium, and uranium in Arizona: Ariz. Bur. Mines Bull. 182, p. 11–41.

Repenning, C. A., and Page, H. G., 1956, Late Cretaceous stratigraphy of Black Mesa, Navajo and Hopi Indian Reservations, Arizona: Am. Assoc. Petroleum Geologists Bull., v. 40, no. 2, p. 255–294.

Swanson, V. E., 1972, Composition and trace-element content of coal and power plant ash: U.S. Dept. Interior, Pt. 2, Appendix J, Southwest Energy Study, Coal Resources Work Group, 61 p.

Turekian, K. K., and Wedepohl, K. H., 1961, Distribution of the elements in some major units of the Earth's crust: Geol. Soc. Am. Bull., v. 72, no. 2, p. 175-191.

Williams, G. A., 1951, The coal deposits and Cretaceous stratigraphy of the western part of Black Mesa: Univ. Arizona (Tucson), unpub. PhD thesis, 307 p.

ARIZONA BUREAU OF MINES

W. H. Dresher, Director

W. W. Fisher, Assistant Metallurgist
J. D. Forrester, Director Emeritus
S. B. Keith, Geologist
R. T. Moore, Principal Geologist
R. T. O'Haire, Associate Mineralogist
H. W. Peirce, Geologist
D. D. Rabb, Mining Engineer
G. H. Roseveare, Metallurgist Emeritus
Samuel Rudy, Assistant Metallurgist
J. S. Vuich, Assistant Geologist

The Arizona Bureau of Mines was created in 1915 by an act of the State legislature and placed under the authority of the Arizona Board of Regents. Under the enabling legislation, the Bureau regularly provides service in the fields of geology, metallurgy, and mining in response to both public inquiries and requirements of other State agencies. In order to carry out these diverse functions, two basic divisions have been established in the Bureau.

GEOLOGICAL SURVEY BRANCH

This branch is charged with the responsibility of acquiring, disseminating, and applying basic geologic data that are designed to (a) enhance our understanding of Arizona's general geologic and mineralogic history and to assist in determining the short and long range influence these have on human activity and the relative merits of alternative land use plans, and (b) assist in developing an understanding of the controls influencing the location of both metallic and nonmetallic mineral resources and mineral fuels in Arizona.

MINERAL TECHNOLOGY BRANCH

This branch conducts research and investigations into, and provides information about the development of Arizona's mineral resources, including the mining, metallurgical processing, and utilization of metallic and nonmetallic mineral deposits. These activities are directed toward the efficient recovery of Arizona's mineral resources as well as insuring that the recovery methods will be compatible with the environmental aspects of the state.

1-3/77SH15/500