



Quality of Economically Extractable Coal Beds in the Gillette Coal Field as Compared With Other Tertiary Coal Beds in the Powder River Basin, Wyoming and Montana

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ABSTRACT

The Powder River Basin, and specifically the Gillette coal field, contains large quantities of economically extractable coal resources. These coal resources have low total sulfur content and ash yield, and most of the resources are subbituminous in rank. A recent U.S Geological Survey study of economically extractable coal in the Gillette coal field focused on five coal beds, the Wyodak rider, Upper Wyodak, Canyon, Lower Wyodak-Werner, and Gates/Kennedy. This report compares the coal quality of these economically extractable coal beds to coal in the Wyodak-Anderson coal zone in the Powder River Basin and in the Gillette coal field (Flores and others, 1999) and other produced coal in the Gillette coal field (Glass, 2000). The Upper Wyodak, Canyon, and Lower Wyodak/Werner beds are within the Wyodak-Anderson coal zone. Compared with all coal in the Wyodak-Anderson coal zone, both throughout the Powder River Basin and just within the Gillette coal field; the thick, persistent Upper Wyodak coal bed in the Gillette coal field has higher mean gross calorific value (8,569 Btu/lb), lower mean ash yield (5.8 percent), and lower mean total sulfur content (0.46 percent).

INTRODUCTION

The U.S. Geological Survey (USGS) has recently conducted a study of economically extractable coal in the Gillette coal field, in the Wyoming part of the Powder River Basin (fig. 1). The study, concentrates on those coal beds that are most likely to be mined given such considerations as coal quality, coal thickness, stripping ratio, land use, environmental and technologic restrictions, and the economics of mining, transport, and current market value. Detailed information on other recent USGS studies, which used similar criteria for determining economically extractable coal in selected study areas, can be found in publications by Molnia and others, 1997, and Osmonson and others, 2000. A major factor in determining coal development potential is coal quality, because if the coal has high sulfur content, high ash yield, or certain trace element content, it may require cleaning and/ or processing before it could be utilized, which may make the coal

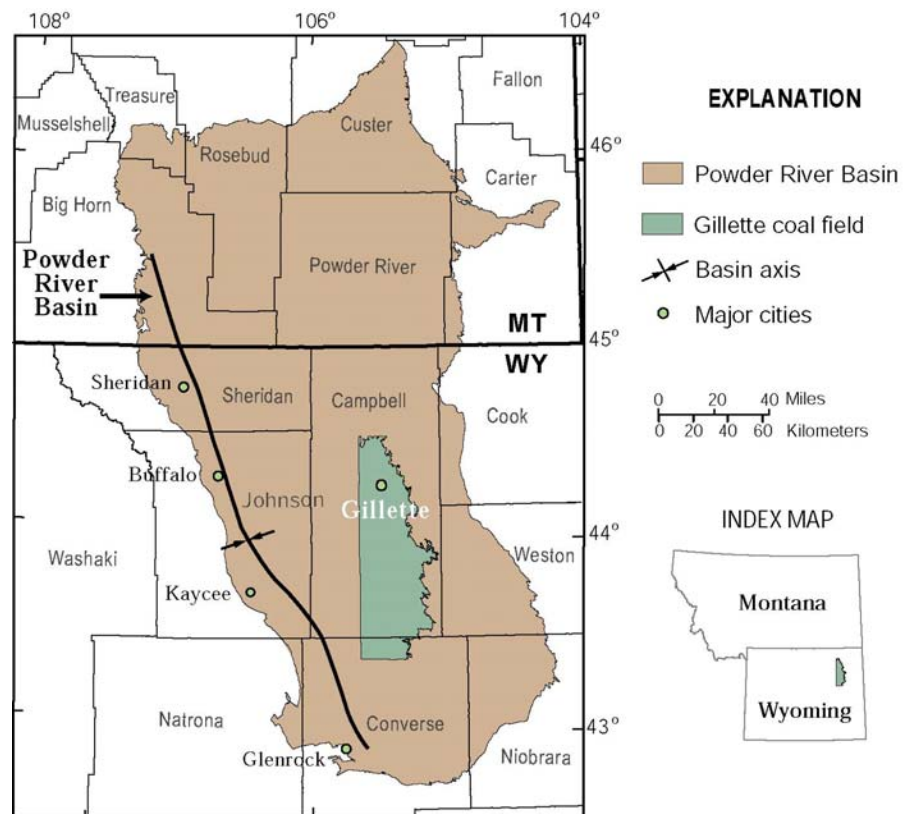


Figure 1. Map of the Powder River Basin, Wyoming and Montana showing the basin axis, counties, major cities, and the Gillette coal field.

uneconomic for development.

Most coal currently being mined is used for electric power generation. Each coal-fired power plant is designed to work with coal beds that have specific ranges in calorific values [British thermal units (Btu)], concentrations of sulfur, and ash yield. Coal that does not fit the requirements of the power plant, because it has high sulfur content, must be cleaned or blended with other coal to meet power plant specifications for utilization. Additionally, the U.S. Clean Air Act Amendment (U.S. Environmental Protection Agency, 1996) has set new Federal regulations on sulfur dioxide emissions. Current standards limit flue-gas emissions from coal-fired power plants to no more than 1.24 pounds of sulfur dioxide per million Btu (lb SO₂/mmBtu). The lb SO₂/mmBtu is a calculated value using the sulfur content of the coal (in percent) and the calorific value (in Btu) of the coal. The quality of coal, especially the sulfur content, is therefore a very important factor in determining what coal is economic for development.

The gross calorific value of Tertiary coal in the Powder River Basin, and specifically of the coal beds studied by the U.S. Geological Survey (USGS) in the Gillette coal field, is relatively low compared with the gross calorific value of coal from most other parts of the United States. Although the Gillette coal has relatively low calorific value, it has much lower sulfur content and lower ash yield than coal from most other parts of the country. Many power plants can use coal with lower gross calorific values; therefore the Gillette coal is in high demand because it does not require cleaning and it can be utilized either exclusively or be blended with other coal to meet utilization specifications. Mines located within the Gillette study area (fig. 2) produced about 305 million short tons of coal, or about one third of the total national production, in 1999 (Resource

Data International, Inc., 2000).

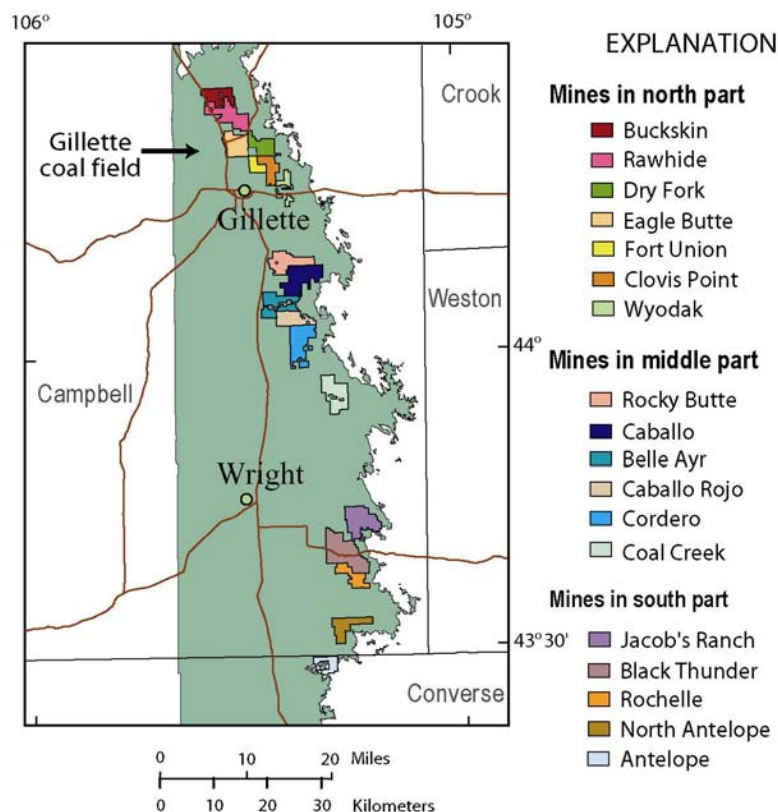


Figure 2. Location of coal mines in the Gillette coal field (modified from Ellis and others, 1999).

The comparison of coal quality, which follows a general discussion of geology in the Powder River Basin (fig. 1), is organized with the discussion progressing from a regional overview to a detailed picture of the economically extractable coal beds recently studied in the Gillette coal field. Coal quality data is compiled from a variety of sources and consists of data on Wyoming coal, Wyodak-Anderson coal in the Powder River Basin, Wyodak-Anderson coal in the Gillette coal field, produced coal from mines in the Gillette coal field (fig. 2), and the five coal beds from the USGS study in the Gillette coal field.

AREA AND GEOLOGY OF THE POWDER RIVER BASIN AND GILLETTE COAL FIELD

Minable coal discussed in this study is within the Tongue River Member of the Fort Union Formation in the Powder River Basin of Wyoming and Montana (fig. 3). The Powder River Basin is an asymmetrical structural basin with an axis that trends northwest-southeast (fig. 1) on the western side of the basin. The basin was formed during Late Laramide time by uplift of surrounding areas (including the Bighorn uplift to the west; the Casper arch, Laramie Range, and Hartville uplift to the south; and the Black Hills uplift to the east) and subsequent subsidence within the basin area (Curry, 1971; Perry and Flores, 1994).

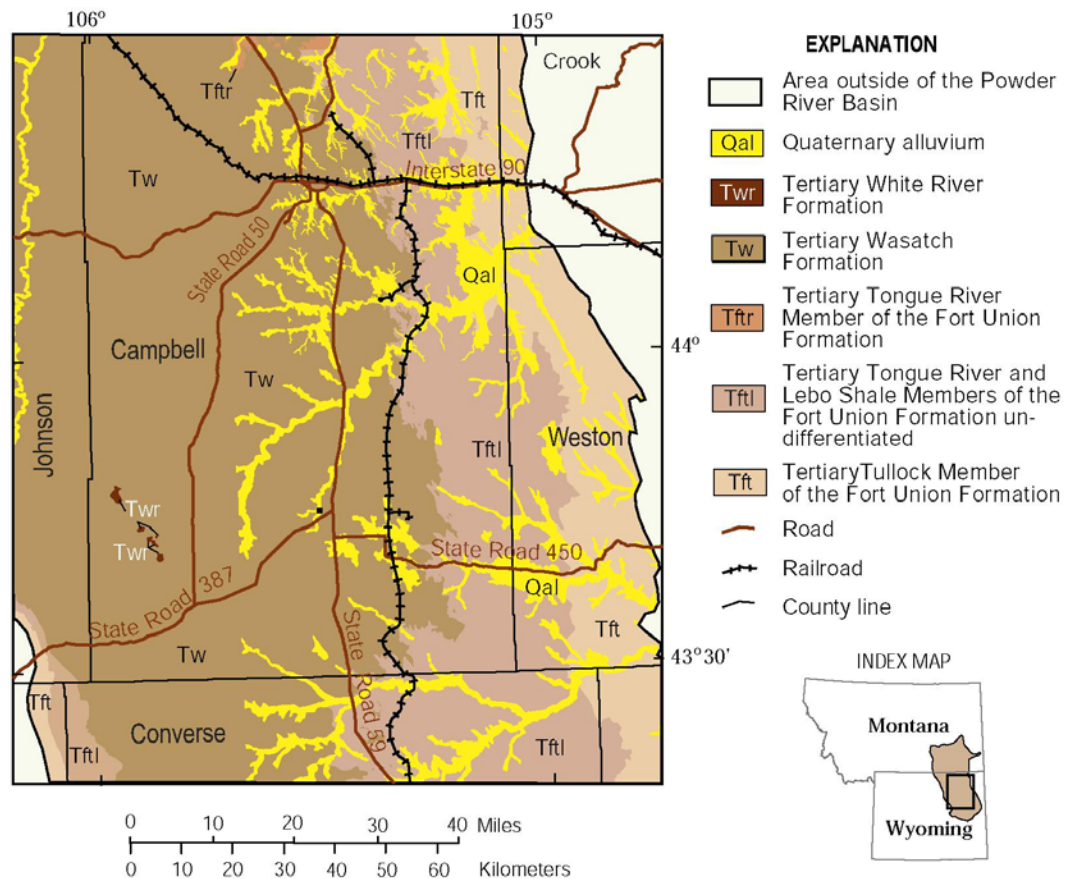


Figure 3. Map showing generalized geology in the part of the Powder River Basin around the Gillette coal field (modified from Ellis and others, 1999).

The basin, as defined by this study, is delineated by the contact between the Tertiary Fort Union Formation and the Late Cretaceous Hell Creek, Fox Hills, and Lance Formations, and Pierre Shale, on the northwest, west, south and east sides of the basin. In the north and northeast the basin boundary is defined by the course of the Yellowstone River. The Powder River Basin covers more than 22,000 sq mi (56,980 sq km) in Wyoming and Montana.

The Fort Union Formation is more than 5,200 ft (1,585 m) thick in the deepest part of the basin. This formation is overlain by exposures of the Eocene Wasatch Formation, in the central part of

the basin. Fort Union rocks dip an average of 20 to 25 degrees to the east along the western margin of the basin, and dip an average of 2 to 5 degrees to the west along the eastern margin of the basin. The formation consists of sandstone, shale, mudstone, and coal, and is divided into (from top to base) the Tongue River, Lebo Shale, and Tullock Members, based primarily on lithology, thickness, and color. The variations in Fort Union Formation rock types and characteristics are controlled by source material, environments of deposition, and influences on the sediment subsequent to deposition.

Fort Union coal in the Powder River Basin developed from peat accumulations in mires located adjacent to fluvial drainages. Most of the coal formed in thick, discontinuous, pod-like peat mires that were split continually by converging and diverging fluvial channels (Flores, 1986; Fort Union Coal Assessment Team, 1999). This resulted in a complex relationship of coal beds, indicated by the merging, splitting, and pinching-out of the beds over short distances.

The Gillette coal field is on the eastern edge of the Powder River Basin, Wyoming (fig. 1). The coal field boundary used for this study is very similar to the Gillette coal field area that was defined by USGS geologists in the past (Keefer and Schmidt, 1973; Denson and Keefer, 1974; Fort Union Coal Assessment Team, 1999) and was selected to include areas of active mines and adjacent areas where there is a potential for future coal development. The eastern boundary of the coal field is delineated by the outcrop of Wyodak-Anderson coal; mapped extent of Wyodak-Anderson clinker; or where that data is not present, the contact of the Wasatch Formation and the Fort Union Formation (Heffern and others, 1993; Heffern and Coates, 1997; Boyd and Ver Ploeg, 1997; Kent and others, 1980; and Coates and Heffern, 2000). The northern boundary is between T. 53 N. and T. 52 N. This boundary is about 5 mi (8 km) north of the Buckskin Mine (fig. 2). The southern boundary is between T. 40 N. and T. 39 N. The southernmost mine included in the coal field is the Antelope Mine (fig. 2). The western edge of the coal field is between R. 74 W. and R. 73 W. The western boundary is about 10 mi (16 km) from the westernmost mine in the Gillette coal field. The coal field encompasses about 1,500 sq mi (3,885 sq km).

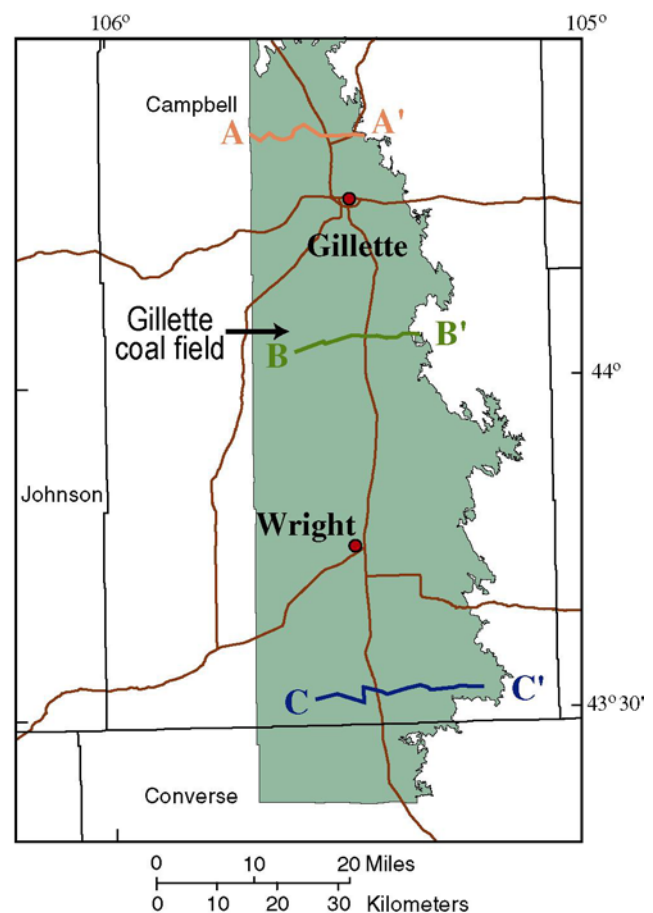


Figure 4. Map showing the location of stratigraphic cross sections through the north, middle and south parts of the Gillette coal field.

The Gillette coal field can be divided into northern, middle, and southern parts. West-to-east trending cross-sections, the locations of which are shown in figure 4, show examples of the lateral variations of Tertiary coal in the Gillette coal field (figs. 5, 6, and 7). On all three cross sections the coal beds split to the west and merge into one or more thick beds to the east. In the northern

part of the coal field the correlation of coal beds is particularly difficult because there are many splits in the coal and beds are discontinuous where peat in the original coal swamp was eroded by contemporaneous fluvial channels. Coal beds in the middle and southern parts of the coal field are much more laterally continuous.

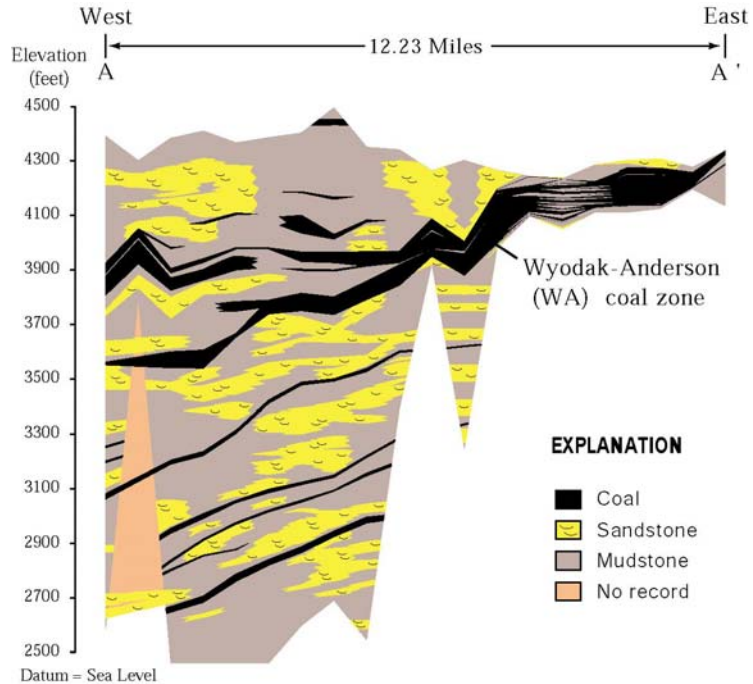


Figure 5. West to east structural cross section through the northern part of the Gillette coal field (modified from Flores and others, 1999). See figure 4 for location.

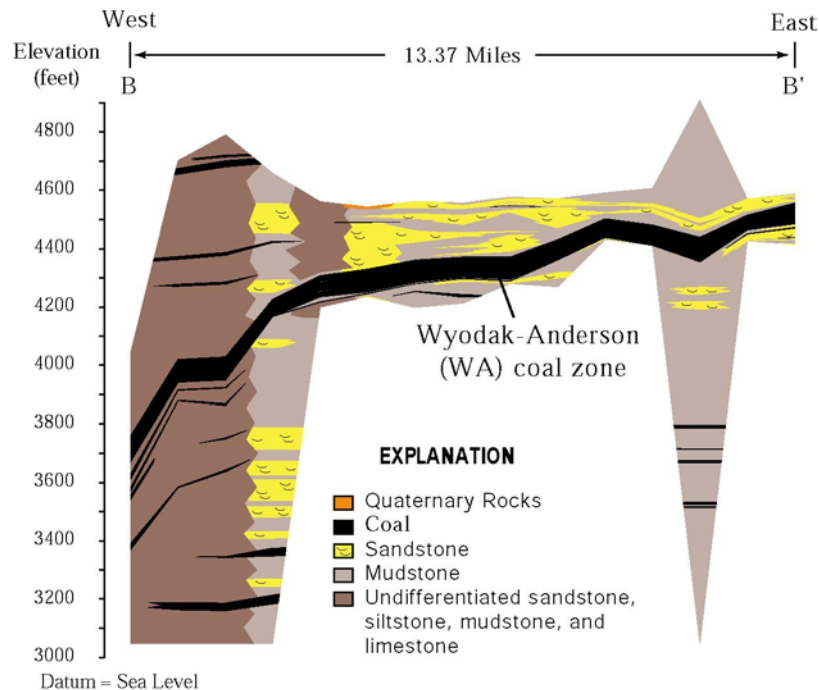


Figure 6. West to east cross section through the middle part of the Gillette coal field (modified from Flores and others, 1999). See figure 4 for location.

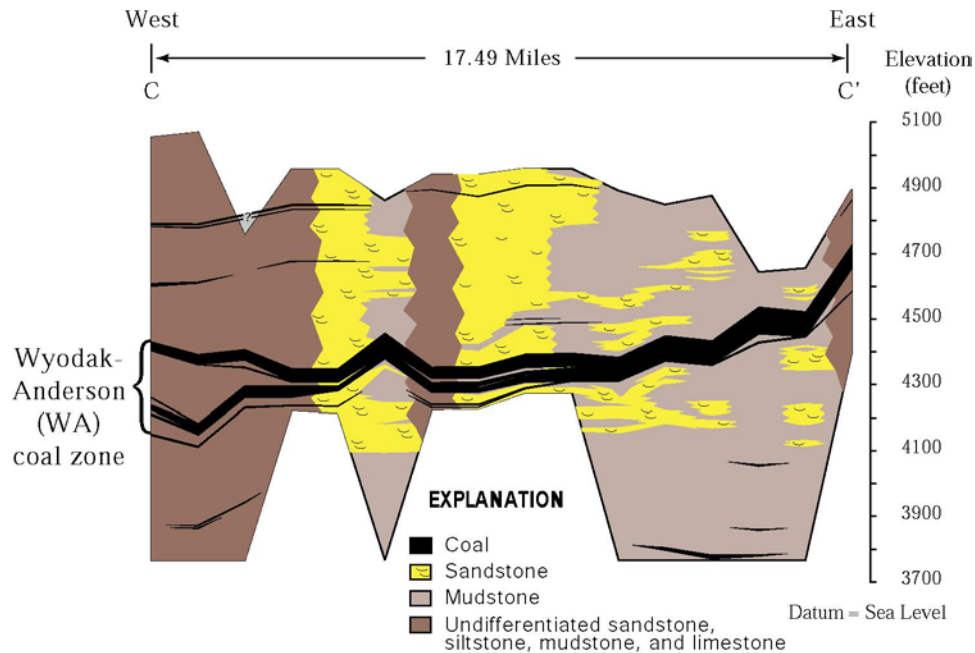


Figure 7. West to east structural cross section through the southern part of the Gillette coal field (modified from Flores and others, 1999). See figure 4 for location.

WYOMING COAL CHARACTERISTICS AND COAL QUALITY

Coal in Wyoming typically ranges in apparent rank from subbituminous to high-volatile A bituminous. The subbituminous coal is Tertiary or Cretaceous in age and occurs in almost all of the coal basins. Almost all bituminous coal is Cretaceous in age, although some deeply buried late Paleocene coal is also bituminous. Generally, older coal beds are higher in apparent rank, but high coal rank is more a factor of depth of burial (greater degree of metamorphism of the peat due to higher geothermal gradient and overlying pressure) than of age. The apparent rank of coal is classified based on its calorific value on a moist, mineral-matter free Btu (mmmfBtu) basis, percent of fixed carbon and volatile matter on a dry, mineral-matter-free basis, and its agglomerating characteristics (Wood and others, 1983, table 1). According to Wood and others (1983) subbituminous coal ranges from 8,300 to 11,500 mmmfBtu and is non-agglomerating, and bituminous coal ranges from 10,500 to 14,000 mmmfBtu and is commonly agglomerating. The gross calorific values (Btu) of coal produced from various coal fields in Wyoming are shown in Table 1. According to Glass (2000) coal being mined in the Powder River Basin ranges from about 7,420 to 10,410 Btu and is subbituminous in apparent rank.

Higher rank bituminous coal in Wyoming generally has moisture content less than 15 percent, volatile matter content between 30 and 40 percent, and fixed carbon content greater than 40 percent. The lower rank subbituminous coal has moisture content between 20 and 30 percent and volatile matter and fixed carbon content of about 30 percent (Glass, 2000).

Ash yield and sulfur content in coal is related to the depositional environment in which the peat accumulated and the volume and type of sediment deposited in the peat. According to Wood and

others (1983), sulfur content and ash yield can be divided into high, medium, and low categories. The values for these categories are shown in table 2. Ash yield and sulfur content of the Paleocene coal mined from the Powder River Basin tends to be low, but ash yield and sulfur content for coal of all ages and throughout the state of Wyoming varies greatly. Sulfur content, ash yield, and trace element content in Cretaceous coal is generally higher than that found in Tertiary coal. These higher values in Cretaceous coal are probably caused by the influx of marine sediment into Cretaceous peat swamps (Flores and others, 1994). In low sulfur coal the form of sulfur is primarily organic, whereas in the high sulfur coal it is mainly pyritic. Much of the pyritic sulfur can be removed from coal mechanically through cleaning processes.

Table 1. Summary of the apparent rank and calorific value of mined coal from coal fields in Wyoming. Btu is British thermal units. Modified from Glass (2000)

Coal field	Apparent coal rank	Range of gross calorific value (Btu/lb)	Mean of gross calorific value (Btu/lb)
Powder River-NW	Subbituminous	9,000-10,410	9,410
Powder River-East	Subbituminous	7,420-9,600	8,580
Powder River- South	Subbituminous	7,610-8,870	7,710
Hanna	Subbituminous and bituminous	8,310-12,600	11,030
Green River	Subbituminous	9,290-10,000	9,480
Hams Fork	Subbituminous	9,270-10,000	9,570
Bighorn	Bituminous	10,730-11,246	10,970

Table 2. Designation of low, medium, and high categories for total sulfur content and ash yield in coal, as defined in Wood and others, 1983

Coal quality parameter	Low	Medium	High
Total sulfur (percent)	Less than 1	1 to 3	Greater than 3
Ash yield (percent)	Less than 8	8 to 15	Greater than 15

WYODAK-ANDERSON COAL CHARACTERISTICS AND COAL QUALITY IN THE POWDER RIVER BASIN, WYOMING AND MONTANA

Coal included in this study in the Gillette coal field, Wyoming is primarily within the Wyodak-Anderson coal zone that was defined by the Fort Union Assessment Team (1999) in their study of coal in the Powder River Basin of Wyoming and Montana. According to their data, the Wyodak-Anderson coal zone in the Powder River Basin has a maximum net coal thickness, defined as the summed thickness of all coal beds greater than 2.5 ft (0.76 m) thick, of 284 ft (86.6 m). The entire zone is more than 600 ft (183 m) thick, measured from the top of the uppermost coal to the base of the lowermost coal, in the central part of the basin. The zone contains up to six coal beds

in a given location. Coal beds average 25 ft (7.6 m) in thickness, and are separated by clastic sedimentary rocks ranging from a few feet to 150 ft (45.7 m) in thickness.

Wyodak-Anderson coal is generally considered to be clean, and compliant with SO₂ emissions standards (U.S. Environmental Protection Agency, 1996). Arithmetic mean values of the Wyodak-Anderson coal from samples collected from 300 locations throughout the Powder River Basin indicate that the coal contains low percentages of total sulfur and has a low ash yield (table 3).

Table 3. Coal quality summary data for Wyodak-Anderson coal in the Powder River Basin, Wyoming and Montana. The table was modified from Stricker and Ellis (1999). Proximate and ultimate analyses are reported on an as-received basis. Trace elements are reported in parts per million and are reported on a whole-coal and remnant-moisture basis. L indicates that the value was below the detection limit for the measuring device

Coal quality parameter	Number of samples	Range		Mean
		Minimum	Maximum	
Moisture (percent)	300	14.50	42.30	27.66
Ash (percent)	279	2.86	25.06	6.44
Total sulfur (percent)	279	0.06	2.40	0.48
Gross calorific value (Btu)	277	3,740	9,950	8,220
LbSO ₂ /million Btu	277	0.14	7.88	1.24
Moist, mineral-matter free Btu	277	4,580	10,560	8,820
Antimony	144	0.01L	17	0.49
Arsenic	158	0.20L	19	2.6
Beryllium	151	0.078L	3.3	0.54
Cadmium	151	0.007L	3.0	0.21
Chromium	161	0.59L	50	6.1
Cobalt	160	0.38L	27	1.9
Lead	162	0.50L	17	3.0
Manganese	161	0.18	210	26
Mercury	162	0.006L	27	0.13
Nickel	161	0.71L	35	4.6
Selenium	151	0.08L	16	1.1
Uranium	157	0.11L	12	1.3

Original analytical data from which these values were calculated consists of proximate and ultimate analyses and trace element analyses from the U.S. Geological Survey COALQUAL database (Bragg and others, 1994). Table 3 reports a range in Wyodak-Anderson total sulfur content of 0.06 to 2.4 percent with a mean of 0.48 percent, and a range in ash yield of from 2.86 to 25.06 percent with a mean of 6.44 percent. Pounds of SO₂ per million Btu for Wyodak-Anderson coal ranged from 0.14 to 7.88 with a mean of 1.24 and the gross calorific value of the coal ranged from 3,740 to 9,950 Btu/lb, with a mean of 8,220 Btu/lb

CHARACTERISTICS AND QUALITY OF WYODAK-ANDERSON AND OTHER COAL IN THE GILLETTE COAL FIELD, WYOMING

The Wyodak-Anderson coal zone in the Gillette coal field includes (from upper to lower) the Smith, Swartz, Anderson, Wyodak, Canyon, and Werner coal beds (Ellis and others, 1999). These beds are in the late Paleocene Tongue River Member of the Fort Union Formation (fig. 3). Wyodak-Anderson coal quality in the Gillette coal field study area (tables 4, 5, and 6) is very similar to that shown for the Wyodak-Anderson coal throughout the Powder River Basin (table 3).

Table 4. Coal quality summary data using weighted averages, one value for each parameter at each data point location, for Wyodak-Anderson coal in the Gillette coal field. The table was modified from Ellis and others (1999). Proximate and ultimate analyses are reported on an as-received basis. Trace elements are reported in parts per million. L indicates that the value was below the detection limit for the measuring device

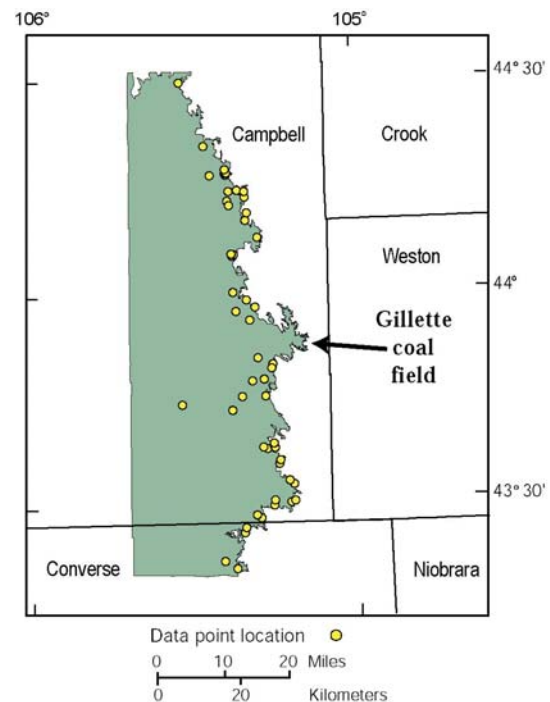


Figure 8. Map showing locations in the Gillette coal field where samples from the Wyodak-Anderson coal zone were collected for coal quality analyses (modified from Ellis and others, 1999).

Coal Quality Parameter	Number of samples	Range		Mean
		Minimum	Maximum	
Moisture (percent)	108	14.5	42.30	27.47
Ash (percent)	87	3.5	25.06	7.45
Total sulfur (percent)	87	0.20	1.16	0.48
Gross calorific value (Btu)	85	3,740	9,950	8,220
LbSO ₂ /million Btu	85	0.44	3.27	1.25
Moist, mineral-matter free Btu	85	4,580	10,560	8,910
Antimony	49	0.01L	17	0.72
Arsenic	62	0.20L	19	2.3
Beryllium	64	0.078L	3.3	0.35
Cadmium	56	0.007L	3.0	0.39
Chromium	65	0.59L	50	7.0
Cobalt	65	0.38L	27	2.3
Lead	66	0.50L	17	2.9
Manganese	66	0.18	210	22
Mercury	66	0.006L	27	0.17
Nickel	66	0.71L	35	5.0
Selenium	56	0.08L	16	1.4
Uranium	61	0.11L	12	1.5

In the Gillette coal field there were a total of 108 locations from which samples were collected. Non-confidential data point locations in the coal field are shown in figure 8. Table 4 shows summary data for Wyodak-Anderson coal in the Gillette coal field. The values shown in this table are weighted averages of Wyodak-Anderson coal quality data at each of the 108 data point locations, one value for each coal quality parameter at each data point location. The table shows total sulfur content that ranged from 0.20 to 1.16 percent with a mean of 0.48 percent and ash yield that ranged from 3.5 to 25.06 percent with a mean of 7.45 percent. Pounds of SO₂ per million Btu for Wyodak-Anderson coal in the coal field ranged from 0.44 to 3.27 with a mean of 1.25 and the gross calorific value of the coal samples ranged from 3,740 to 9,950 Btu/lb with a mean of 8,220 Btu/lb (Ellis and others, 1999).

Table 5. Proximate, ultimate and calorific values using all sample analyses, more than one sample at each data point location, from coal beds in the Wyodak-Anderson coal zone in the Gillette coal field. Calculated from data in Flores and others (1999) and from confidential sources. All values are reported on an as-received basis. MmmfBtu is moist, mineral-matter free Btu

Chemical parameter	Number of samples	Minimum value	Maximum value	Mean value
Moisture (percent)	226	14.5	42.3	29.16
Ash (percent)	226	2.5	32	7.05
Total sulfur (percent)	227	0.1	4.6	0.54
Gross calorific value (Btu)	161	4,690	9,950	7,870
LbSO ₂ /million Btu	161	0.2	6.43	1.62
MmmfBtu	161	6,940	10,570	8,580
Organic sulfur (percent)	215	0.06	1.55	0.37
Pyritic sulfur (percent)	199	0.01	3.09	0.16
Sulfate sulfur (percent)	187	0.01	0.47	0.03
Fixed carbon (percent)	226	4.1	44.5	33.41
Volatile matter (percent)	226	21.4	55.7	30.38

Table 6. Trace element content of coal samples from beds in the Wyodak-Anderson coal zone in the Gillette coal field. Calculated from data in Flores and others (1999). All values are reported in parts per million and are on a whole-coal and remnant-moisture basis

Chemical parameter	Number of samples	Minimum value	Maximum value	Mean value
Antimony	281	0.01	17	0.34
Arsenic	282	0.23	150	3.3
Beryllium	215	0.02	9.1	0.80
Cadmium	273	0.007	3.0	0.09
Chromium	285	0.59	66	7.2
Cobalt	284	0.27	27	2.1
Lead	286	0.14	20	2.9
Manganese	286	0.18	220	27
Mercury	229	0.006	27	0.11
Nickel	286	0.53	67	5.4
Selenium	273	0.05	16	1.0
Uranium	282	0.01	12	0.98

A more detailed coal quality summary for each of the coal beds sampled from the Wyodak-Anderson coal zone in the Gillette coal field is shown in Tables 5 and 6. These two tables show proximate and ultimate analyses, gross calorific value, and selected trace element content of coal from over 200 sample analyses, more than one sample collected from most data point locations. The values reported for individual samples, shown in Tables 5 and 6, have a much larger range than are reported for the weighted averages, shown in Table 4. This difference in values indicates that the quality of coal produced can be customized through selective mining of coal beds, and blending of coal to meet individual coal quality standards.

About 305 million short tons of coal were supplied to coal-fired powered power plants in 1999 from coal mines in the Gillette coal field (fig. 2). According to the 2000 COALdat database (Resource Data International, Inc., 2000), coal supplied to electrical power plants in 1999 from these mines had mean values of 0.31 percent total sulfur, 5.21 percent ash yield, 0.72 pounds of SO₂ per million Btu, and gross calorific value of 8,630 Btu/lb. Table 7 shows the quality of coal produced from these mines, reported by location of the mines in the northern, middle, and southern parts of the coal field (fig. 2).

Table 7. Summary of coal quality and production of coal from mines in the Gillette coal field supplied to coal-fired power plants in 1999 (Resource Data International, Inc., 2000). Coal quality parameters are listed by the location of the mines within the coal field (fig. 2). The "combined" category is coal that was supplied to power plants from mines located in different parts of the coal field. Proximate, ultimate, and heat of combustion values are reported on an as-received basis. Btu is British thermal units. Production is reported in millions of short tons (mst) and rounded to one decimal place

Coal quality parameter and 1999 production	Northern part	Middle part	Southern part	Combined areas	All mines in Gillette coal field
Minimum ash (percent)	4.37	3.7	3.8	4.22	3.7
Maximum ash (percent)	9.3	45.03	18.9	5.5	45.03
Mean ash (percent)	5.66	5.39	5.11	4.68	5.21
Minimum total sulfur (percent)	0.23	0.21	0.15	0.25	0.15
Maximum total sulfur (percent)	1.05	0.7	5.32	0.4	5.32
Mean total sulfur (percent)	0.45	0.33	0.29	0.32	0.31
Minimum gross calorific value (Btu)	7,940	8,190	8,100	8,300	7,940
Maximum gross calorific value (Btu)	8,790	8,770	9,410	8,850	9,410
Mean gross calorific value (Btu)	8,300	8,430	8,770	8,490	8,630
Minimum lbSO ₂ /million Btu	0.55	0.49	0.34	0.58	0.34
Maximum lbSO ₂ /million Btu	2.53	1.71	12.13	0.95	12.13
Mean lbSO ₂ /million Btu	1.09	0.78	0.66	0.76	0.72
Production (mst)	26.8	94.8	167.0	16.8	305.3

QUALITY OF ECONOMICALLY EXTRACTABLE COAL BEDS ASSESSED IN THE GILLETTE COAL FIELD STUDY

The recent USGS study of economically extractable coal in the Gillette coal field concentrated on five coal units. These units are currently designated, from upper to lower, as the Wyodak rider, Upper Wyodak, Canyon, Lower Wyodak/Werner, and Gates/Kennedy. The Wyodak rider is equivalent to the Smith bed of Kent and others (1980) and the Roland/Badger of Pierce and others (1990). The Upper Wyodak is the same as the Upper Wyodak of Kent and others (1980). The Canyon is equivalent to the Canyon of Kent and others (1980), which is an upper split of the lower Wyodak/Werner. The lower Wyodak/Werner is equivalent to the lower Wyodak of Kent and others (1980), which includes the Werner of Pierce and others (1990). The Gates/Kennedy coal is equivalent to the Gates of Kent and others (1980) and the upper Kennedy of Pierce and others (1990). Glass (2000) contains a fence diagram, modified from several U.S. Geological Survey publications, in which many of the coal bed correlations and bed names used in various parts of the Powder River Basin are clarified. This fence diagram shows the Anderson bed as equivalent to what is called the Upper Wyodak, the Gates coal as being equivalent to the Wall, and the Kennedy coal as equivalent to the Pawnee.

To summarize, the coal units included in the Gillette study area are stratigraphically equivalent to (from uppermost to lowermost) the Roland, Smith, Badger, Wyodak, Anderson, Canyon, Werner, Gates or Wall, and Kennedy or Pawnee coal beds as defined in previous publications. All of these coal beds are subbituminous C in apparent rank. According to data from the recent study and from statistics reported in Glass (2000), the coal beds included have a maximum thickness of about 200 ft (61 m), contain from 15 to 35 percent moisture and 0.13 to 2.3 percent total sulfur, have an ash yield of from 2.5 to 19.68 percent, have gross calorific values from 7,130 to 9,950 Btu/lb, and have calculated values for pounds of sulfur dioxide per million Btu's that range from 0.25 to 3.68.

The data set used for this coal quality study of the economically recoverable coal beds in the Gillette coal field included analytical data from published sources (Bragg and others, 1994; Flores and others, 1999) and unpublished confidential data from various sources. The data set is made up of 140 samples for which proximate and ultimate analyses and heat of combustion were run on an as-received basis and 157 samples that were analyzed for content of potentially hazardous trace elements, measured in parts per million on a whole-coal and remnant-moisture basis. A summary of the coal quality data is shown in Tables 8 and 9. The data set does not include analyses for the Canyon or Gates/Kennedy coal, but Table 8 includes data for the Canyon bed from Glass (2000).

Table 8. Proximate and ultimate analyses and calorific values of economically extractable coal in the Gillette coal field. Proximate and ultimate analyses are reported in percent by weight. All analyses are reported on an on an as-received basis. No data was available for the Gates/Kennedy coal bed

Parameter	Data	Wyodak rider	Upper Wyodak	Lower Wyodak/Werner	Wyodak rider, Upper Wyodak, and Lower Wyodak/Werner combined	Canyon (Glass, 2000)
Moisture	Number of samples	4	127	9	140	9
	Minimum (percent)	20	15	25	15	26.5
	Maximum (percent)	27	35	32	35	31.5
	Mean (percent)	23	27	27	27	29.6
Ash	Number of samples	4	127	9	140	9
	Minimum (percent)	9.7	2.5	4.2	2.5	3.1
	Maximum (percent)	19.1	19.68	8.2	19.68	7.4
	Mean (percent)	12.90	5.80	5.83	6.01	5.1
Total sulfur	Number of samples	4	127	9	140	9
	Minimum (percent)	0.80	0.13	0.20	0.13	0.14
	Maximum (percent)	1.50	2.30	0.40	2.30	0.92
	Mean (percent)	1.13	0.46	0.27	0.46	0.34
Organic sulfur	Number of samples	4	116	9	129	
	Minimum (percent)	0.39	0.06	0.15	0.06	
	Maximum (percent)	0.83	1.10	0.37	1.10	
	Mean (percent)	0.60	0.32	0.23	0.32	
Pyritic sulfur	Number of samples	4	103	8	115	
	Minimum (percent)	0.07	0.01	0.01	0.01	
	Maximum (percent)	1.09	1.63	0.04	1.63	
	Mean (percent)	0.56	0.14	0.03	0.15	
Sulfate sulfur	Number of samples	1	96	8	105	
	Minimum (percent)	0.01	0.01	0.01	0.01	
	Maximum (percent)	0.01	0.47	0.03	0.47	
	Mean (percent)	0.01	0.03	0.02	0.03	
Lb SO ₂ /million Btu	Number of samples	4	62	9	75	
	Minimum	0.35	0.25	1.45	0.25	
	Maximum	0.71	3.68	3.02	3.68	
	Mean	0.55	1.70	2.40	1.73	
Gross calorific value	Number of samples	4	62	9	75	9
	Minimum (Btu)	7,890	7,170	7,580	7,170	7,540
	Maximum (Btu)	9,410	9,950	8,980	9,950	8,610
	Mean (Btu)	8,500	8,570	8,470	8,550	8,290
Moist, mineral-matter free Btu	Number of samples	4	62	9	75	
	Minimum	9,160	8,250	8,310	8,250	
	Maximum	10,560	10,570	9,410	10,570	
	Mean	9,880	9,190	9,040	9,210	
Fixed carbon	Number of samples	4	127	140	9	9
	Minimum (percent)	29.7	25.5	4.1	31.8	4.1
	Maximum (percent)	33.1	44.5	44.5	38.4	39.3
	Mean (percent)	30.8	35.0	34.8	34.6	33.6
Volatile matter	Number of samples	4	127	9	140	9
	Minimum (percent)	30.30	24.75	28.80	24.75	28.7
	Maximum (percent)	37.80	37.80	55.70	55.70	33.3
	Mean (percent)	33.23	31.71	33.50	31.87	30.7

Table 9. Values for potentially hazardous air pollutant trace elements in economically extractable coal in the Gillette coal field. Reported in parts per million on a whole-coal and remnant-moisture basis. No data was available for the Canyon or Gates/Kennedy coal beds

Parameter	Data	Wyodak rider	Upper Wyodak	Lower Wyodak/ Werner	All three coal beds
Antimony	Number of samples	4	138	10	152
	Minimum	0.52	0.01	0.09	0.01
	Maximum	1.2	2.7	1.04	2.7
	Mean	0.76	0.21	0.38	0.24
Arsenic	Number of samples	4	139	10	153
	Minimum	3.6	0.35	0.33	0.33
	Maximum	65	30	3	65
	Mean	20	2.1	0.88	2.5
Beryllium	Number of samples	4	118	9	131
	Minimum	1.4	0.03	0.17	0.03
	Maximum	4.2	9.1	1.7	9.1
	Mean	2.4	0.51	0.44	0.56
Cadmium	Number of samples	4	133	10	147
	Minimum	0.09	0.01	0.03	0.01
	Maximum	0.52	0.72	0.12	0.72
	Mean	0.25	0.07	0.05	0.07
Chlorine	Number of samples	4	107	9	120
	Minimum	50	50	50	50
	Maximum	50	700	50	700
	Mean	50	157	50	146
Chromium	Number of samples	4	143	10	157
	Minimum	14	0.81	1.7	0.81
	Maximum	19	35	12	35
	Mean	17	4.7	5.2	5.02
Cobalt	Number of samples	4	143	10	157
	Minimum	3.2	0.28	0.71	0.28
	Maximum	9.7	11	11	11
	Mean	5.8	1.8	3.9	2.01
Lead	Number of samples	4	143	10	157
	Minimum	2.4	0.14	0.76	0.14
	Maximum	7.7	14	7.6	14
	Mean	5.04	2.5	2.9	2.5
Manganese	Number of samples	4	143	10	157
	Minimum	15	2.7	2.5	2.5
	Maximum	85	86	17	86
	Mean	44	16	8.3	16
Mercury	Number of samples	4	86	10	100
	Minimum	0.14	0.02	0.02	0.02
	Maximum	0.35	3.8	0.16	3.8
	Mean	0.26	0.21	0.07	0.20
Nickel	Number of samples	4	143	10	157
	Minimum	13	0.85	1.5	0.85
	Maximum	21	39	9.3	39
	Mean	17	5.1	6.2	5.5
Selenium	Number of samples	4	136	8	148
	Minimum	1.5	0.05	0.18	0.05
	Maximum	2.2	6.7	1.7	6.7
	Mean	1.8	1.01	0.59	1.01
Uranium	Number of samples	4	139	10	153
	Minimum	1.4	0.08	0.01	0.01
	Maximum	2.9	3.2	1.2	3.2
	Mean	2.1	0.61	0.46	0.64

The Upper Wyodak coal in the Gillette coal field is of particular interest for future development, because it is laterally pervasive and reaches a maximum thickness of about 200 ft (61 m). The Upper Wyodak coal bed also has higher mean gross calorific value (8,569 Btu/lb), lower mean ash yield (5.8 percent), and lower mean total sulfur content (0.46 percent) than most other Wyodak-Anderson coal beds in the Gillette study area (Tables 8 and 10).

Table 10. Comparison of coal quality of the Wyodak-Anderson coal in the Powder River Basin and in the Gillette coalfield (Flores and others, 1999; Ellis and others, 1999), and of the economically extractable coal beds and the Upper Wyodak coal bed in the Gillette coal field. Proximate, ultimate, and heat of combustion values are reported on an as-received basis. Trace elements are reported on a whole-coal and remnant-moisture basis. Btu is British thermal units; MmmfBtu is moist, mineral-matter free Btu; and ppm is parts per million

Coal quality parameter	Area of study and coal bed(s) analyzed			
	Powder River Basin	Gillette coal field		
	Wyodak-Anderson coal from Flores and others, 1999 (weighted mean)	Wyodak-Anderson coal from Ellis and others, 1999 (weighted mean)	Coal beds assessed for this study (mean)	Upper Wyodak coal bed from this study (mean)
Moisture (percent)	27.66	29.16	27	27
Ash (percent)	6.44	7.05	6.01	5.80
Total sulfur (percent)	0.48	0.54	0.46	0.46
Gross calorific value (Btu)	8,220	7,874	8,554	8,569
MmmfBtu	8,820	8,581	9,211	9,193
Organic sulfur (percent)	---	0.37	0.32	0.32
Pyritic sulfur (percent)	---	0.16	0.15	0.14
Sulfate sulfur (percent)	---	0.03	0.03	0.03
Fixed carbon (percent)	---	33.41	34.8	35.0
Volatile matter (percent)	---	30.38	31.87	31.71
Arsenic (ppm)	2.6	3.3	2.5	2.1
Mercury (ppm)	0.13	0.11	0.20	0.21
Selenium (ppm)	1.1	1.0	1.01	1.01
Uranium (ppm)	1.3	0.98	0.64	0.61

CONCLUSION

Coal in the Powder River Basin, specifically the economically extractable coal in the Gillette coal field, is very desirable for future coal production. The beds are generally thick and relatively close to the surface, making it economic to produce the coal through surface mining operations. The Wyodak-Anderson coal in the Powder River Basin and in the Gillette coal field and five economically extractable beds recently studied also low in total sulfur content and ash yields and

have relatively high gross calorific value, compared with coal from most other coal fields in the U.S. (Flores and others, 1999).

Table 10 shows the quality of coal in the recent study compared with the quality of coal in the Wyodak-Anderson coal zone throughout the Powder River Basin (Stricker and Ellis, 1999) and in the Gillette coal field (Ellis and others, 1999). Wyodak-Anderson coal in the Powder River Basin has relatively low gross calorific value, with a range of 4,580 to 10,560 Btu and a mean of 8,820 Btu. However, the low sulfur content and ash yield for economically extractable coal seams in the Gillette coal field; with a minimum value of 0.13 percent and a mean of 0.46 percent total sulfur and a minimum value of 2.5 percent and a mean of 6.01 percent ash yield (tables 8 and 10); makes it desirable to blend higher quality coal in these coal seams with lower quality coal to meet power plant emissions standards. The Upper Wyodak bed in the recent USGS study is of particular interest for future development, because it is thick, pervasive, and of high quality.

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