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Pyrophoricity (spontaneous combustion) of Powder River Basin coals– Considerations for coalbed methane development

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INTRODUCTION

Natural coal fires along coal outcrops in the Powder River Coal Field or Powder River Basin (PRB) have occurred throughout the more recent geologic history of the area. Researchers using modern fission-track dating techniques on the baked and fused rock associated with ancient fires have dated in-place coal burn areas as old as middle Pliocene (2.8 ± 0.6 million years before present). Clinker float from a PRB stream gravel terrace has been dated as old as early Pliocene (4.0 ± 0.7 million years before present) (Heffern and others, 1983). Natural coal fires have been major contributors to the formation of the topography and landforms of the basin (Coates and Heffern, 1999). Early Native Americans held these coal fire areas as spiritual lands. Prehistoric inhabitants of the PRB used porcellanite (formed from intensively coal-baked shale or siltstone) for weapon points and tools (Fredlund, 1976).

Early explorers to the area in the early 1800s, such as the Lewis and Clark expedition, noted the presence of wild coal fires in the northern PRB. During the late 1880s and first half of the 1900s, the land in the PRB was homesteaded. These settlers extinguished most of the bigger, well-established fires. Also during this period, shallow underground coal mining began to supply fuel to the region's homesteaders, to blacksmiths, and to support railroads as they moved across the PRB. As these early, shallow underground mines were abandoned, subsidence and related spontaneous coal fires became an environmental concern (Jolley and Russell, 1959). Currently, federal and state agencies continue to fight natural coal fires, extinguishing old fires and keeping new outbreaks from becoming established.

The great boom in PRB coal production began in 1974 and continues today. Large surface mines in the Wyoming portion of the PRB supply the nation with approximately one-third of its annual steam coal needs, thus making Wyoming the number one coal-producing state in the United States (Lyman and Hallberg, 2000). In the last five years an emerging energy resource, coalbed methane (CBM), has created another boom throughout the Powder River Basin. With the recent proliferation of CBM drilling and production, concerned citizens have inquired about the potential for underground coal fires in relation to the CBM extraction process. This paper will briefly review the chemistry of the pyrophoricity (spontaneous combustion) of coal, how these chemical effects apply to natural coal fires, the relationship of coal fires to mining activity, and how these factors apply to the current CBM play in the Powder River Coal Field.

SPONTANEOUS COMBUSTION OF COAL

Spontaneous combustion of coal has long been a concern for mankind. It is known to occur in both surface and underground mines, stockpiles and other coal storage facilities, as well as along natural outcrops of coal. Such spontaneous ignition of coal has impacted the course of history. Spontaneous combustion of coal is now believed to have fueled the explosion and sinking of the USS Maine, the catalysis that launched our country into the Spanish American War (Allen, 1998). It is also been recognized as a contributing factor with other maritime disasters such as the much publicized sinking of the Titanic. Shallow coal fires in areas of abandoned mines are today still a major environmental concern throughout the world. Millions of dollars are annually expended throughout the world to find ways of extinguishing these difficult to control fires.

In the spontaneous combustion of coal, the sources of heating are found in the low temperature of oxidation in combination with absorption of moisture by dried or partially dried coal. The oxidation of coal is a very complex process due to the diverse composition and heterogeneous nature of coal. Simplified, the basic reaction in the oxidation of coal can be written as:

$$\mathbf{C + O_2 = CO_2 + Heat}$$

This chemical reaction is exothermic (about 94 kcal/mole) and the rate of reaction will double for every increase of 10^{o} C (Speight, 1983). If the heat cannot escape it raises the temperature of the coal past its ignition point and a coal fire occurs. It has been shown in the laboratory that low rank, high moisture coals (such as those of the PRB) exhibited self-heating at temperatures as low as 30^{o} C (Kuchta and others, 1980).

In a large-scale study of spontaneous combustion of coal (Smith and others, 1991), the heating effects of oxidation in low rank coals was observed, but in most cases this was not believed to be enough to cause combustion. In an experimental run where combustion did occur, a quantity of dried coal was placed in the center of a pile of "wet " coal. Significantly higher temperatures were recorded at the interface between the dry and wet coal, and this interface was the location along which spontaneous combustion started. This tendency of coal to have an increased level of self-heating while absorbing water had been observed in earlier laboratory scale experiments (Kuchta and others, 1980), and quantified in the work of Bhat and Agarwal (1996).

The above observations point out the importance moisture changes play in the spontaneous combustion of coal. That role concerns what is known as the heat-of-wetting, defined as the heat evolved by physical action when water comes in contact with dry coal. Drying coal is an endothermic process and lowers the temperature of the coal. With the reduction of moisture, it also increases the exposure of more oxidation sites within the coal. Wetting (or gaining moisture) is an exothermic process and the liberated heat can accelerate the spontaneous heating of the coal (Kim, 1977).

While changes in moisture and oxidation can explain most of the spontaneously generated heat in coal, several other key factors have been identified that contribute to the pyrophoricity of coal. Kim (1977) listed these additional factors:

1. **Air flow rate.** This is a complex factor because the flow of air provides both the oxygen necessary for the oxidation process and a way to dissipate the heat as it is generated.
2. **Particle size.** Particle size has an inverse relationship to spontaneous combustion in coal. The smaller the particle size the greater surface area is available on which oxidation can take place.
3. **Rank.** As the rank of coal decreases, the tendency for coal self-heating increases. The subbituminous coals in the PRB contain a high percentage of reactive macerals (vitrinite and exinite) that increases the tendency of coal to self-heat.
4. **Temperature.** The higher the temperature, the faster coal reacts with oxygen.
5. **Pyrite content.** The presence of the sulfur minerals pyrite and marcasite may accelerate spontaneous heating. These minerals may swell upon heating, causing the coal to disintegrate and reducing the particle size involved in the reactions. (Generally, pyrite must be present in concentrations greater than 2% before it has a significant affect.)

6. **Geological factors.** Rocks are poor conductors of heat. Faults and fractures in the overburden can permit water and air to enter a coal seam. This influx of water and oxygen is the reason that abandoned mines, especially those that have suffered subsidence events, often are sites of spontaneous coal fires.
7. **Mining practices.** Several factors in both surface and underground mining can contribute to spontaneous heating of coal. Good housekeeping is at the forefront of most safety programs at coal mines today. Areas within a mine where fine coal particles accumulate, such as at the base of the coal highwall or in gob areas underground, are vulnerable to become sites for potential spontaneous coal fires.

NATURAL FIRES

While spontaneous combustion may occur, the dominant cause of fires along coal outcrops is now recognized as wildfires (**Figure 1**) started by lightning or the carelessness of humans each year (Coates and Heffern, 1999). The rare exception is where mass wasting (slumping, landslides, and rapid erosion associated with major flood events) exposes relatively fresh coal to the atmosphere.

Figure 1. August 6, 2000, on the East Fork of the Bitterroot River at the Sula Complex Fire. Control of this fire by the Alaskan Type I Incident Management Team. Photograph by John McColgan, Bureau of Land Management, Alaska Fire Service.

In their 1999 paper, Coates and Heffern observed that coal above the local water table degasses at a rate that is relative to its distance from a free surface, and to the permeability of the intervening material. They further observed, “By the time the coal is exposed to the air it is too degassed to ignite spontaneously.”

COAL FIRES IN MINES

Spontaneous ignition of coal is extremely common within the large surface mines of the PRB. These mining operations create the perfect environment for the self-heating of coal. The most vulnerable area in a PRB surface mine is at the foot of a coal highwall (**Figure 2**).

Figure 2. Unidentified eastern PRB surface mine, Wyoming State Geological Survey file photograph by Laura L. Hallberg.

Along a coal highwall, fresh coal is exposed and as it dries it sloughs off to form a collection of fine-size coal particles that collect in piles at the base of the highwall. These piles of dry coal form the perfect site for spontaneous combustion. When atmospheric moisture is high and strong winds are present (and the piles of coal are of a volume sufficient to hold the generated heat of oxidation and wetting), coal fires start. The miners control this by spreading out and/or re-compacting the heated coal area, which cuts off oxygen and allows radiation of the heat back into the atmosphere. Rarely does the mine permit the coal fire to spread back into the highwall. The highwall rarely is the site of a coal ignition because the in-place coal consists of much larger sized material, exposing only minimum surface area for the necessary heat-forming reactions. Furthermore, the highwall allows any heat generated to be easily vented to the atmosphere (R.M. Lyman, personal observations and conversations with various technical mining personnel).

While there are no active underground mines in the PRB, abandoned mines continue to be the sites of hard-to-control coal fires. The Acme mine area north of Sheridan, Wyoming is a prime example of these fires (**Figures 3** and **4**).

The old workings of these shallow underground mines have undergone extensive subsidence. Large amounts of air have been introduced to the old workings via tensional fractures propagated to the surface with the rock failure associated with the collapse of the old mine's roof (**Figure 5**). Rib failure and pillar crushing (also related to subsidence) has filled the old mine void with relatively fresh, fine-sized coal particles. Water is introduced both by surface runoff into these same fractures and by seasonal fluctuations of the local groundwater table. These factors combine to give ideal model conditions for coal spontaneous combustion (Coates and Heffern, 1999). Due to the poor thermal conductance of the rock and soil overlying the coal, heat liberated from the reactions cannot readily escape and the coal ignites.

Figure 3. November 1975, eastward aerial oblique view of surface effects of an underground mine fire above the northern part of the Acme mine, Wyoming (from Dunrud and Osterwald, 1980).

Figure 4. Advancing fire front of the Acme underground mine fire. Steam and smoke can usually be seen emanating from cracks in the ground. Photograph by R.W. Jones, September, 1980.

Figure 5. Subsidence pit above collapsed room in the Monarch underground coal mine north of Sheridan, Wyoming. The coal is about 80 feet below the surface but exposure to oxygen and entry of water from this pit and others caused an underground fire. Photograph by R.W. Jones, September, 1980.

Active underground mines also must guard against coal fires. In room and pillar mines, much time is spent cleaning up local rib and roof falls as they occur. Rock dusting the mine ribs and inactive faces prevents the liberation of fine-sized coal particles. Haulageways and belt lines are routinely patrolled to pick up any coal that might have spilled. Often, a novice miner's first job is to "shovel on the belt" (R.M. Lyman, personal experience). Modern ventilation keeps fresh air moving through the mine and automated air-monitoring devices check for levels of coal-combustion waste gases. Each mine has to be inspected by an experienced, certified miner or "fire bossed" on a rigorous schedule dictated by federal mine safety laws.

Mine fires still do occur occasionally in the modern coal mine. The majority of mine fires today are a result of mechanical or electrical failure or miner error rather than from spontaneous combustion of coal. A badly spliced power cable, an overheated belt drive, or other failures can ignite an underground fire.

One area in modern coal mines that is susceptible to fires started by spontaneous combustion is the gob area left behind in a longwall operation. In longwall mining, long panels of coal are mined by using a coal shearer that moves across the face of a coal seam, cutting and dropping the coal directly onto a chain conveyor. The chain conveyor sends the coal to a belt line, which in turn carries the coal out of the mine. The roof is supported by a row of hydraulic shields. As the production face advances, the shields are advanced toward the coal face, allowing the roof to collapse behind the shields. While most of the coal is removed, floor coal, rider (or roof) coals, and other carbonaceous rock types are sometimes left behind and can be subject to self-heating problems (Kim, 1995; Kim and Chaiken, 1993).

IN SITU UNDERGROUND COAL GASIFICATION

Moving further towards coalbed methane considerations, some insight can be drawn from two federally funded *in-situ* underground coal gasification (UCG) experiments that took place in Wyoming during the 1970s.

The first *in situ* UCG project in Wyoming was located in the Hanna Basin two miles south of the town of Hanna, approximately 70 miles northwest of Laramie. A pattern of 16 wells was drilled into the Hanna No. 1 coal seam. Spacing of the wells ranged from 25 to 200 feet. The coal at the test site was approximately 30 feet thick and overlain by 350 to 400 feet of overburden. The Hanna No.1 coal in the test area is a low-sulfur subbituminous coal (Campbell and others, 1974).

In the central well, the coal had to be hydraulically fractured before acceptable communication between the closely spaced wells could be established. All the holes were initially de-watered and air injection into the central well was begun on March 28, 1973. Propane was introduced into the air stream at a 4% mixture and injected at a rate of 101 to 150 psig. These rates were maintained for 20 hours before ignition. The ignition procedure operated for 18 hours before combustion was sustainable by injected airflow (Campbell and others, 1974). However, this forward-burning phase of the experiment had trouble maintaining an acceptable permeability in the burn zone. The ignition borehole had to be “blown off “ before the investigators could inject enough air to sustain the fire. In their conclusions, Campbell and others (1974) stated, “Loss of permeability due to plugging of fissures by tar and combustion products precludes the maintenance of the forward combustion process.”

The second *in situ* UCG study was conducted by the Department of Energy (then known as the U.S. Energy Research and Development Administration) at a test facility located approximately 20 miles south-southwest of Gillette, Wyoming. Known as the Hoe Creek UCG test, the experiment was conducted on the Felix No.2 coal seam in the Wasatch Formation. This program ran between 1976 and 1979, and included a test using forward combustion (as in the Hanna project) to establish the fire. The coal was fractured using heavy explosives to increase the coal permeability, and 10 million standard cubic feet per day of air was injected this time at pressures below the hydrostatic pressure of the seam. After eleven days, it was determined that only about 130 tons of coal had been consumed and forward combustion proved inefficient in sustaining the burn (DOE/EA-1219, 1997).

These two *in situ* coal gasification programs both came to the same conclusion: even under extreme efforts to inject air into the burn zone, the coal burning away from the ignition area (forward combustion) cannot be sustained even in areas where the coal is highly fractured and de-watered.

COALBED METHANE

Coalbed methane is natural gas (CH_4) that has been generated during the coalification process. The coalification process transforms (through time, heat, and pressure) the original dead, buried plant material into the present deposits of coal. CBM gas from the low-rank subbituminous coals in the Powder River Basin consists of 98 to 98.5% methane with 1.5 to 2.0% carbon dioxide (CO_2). Higher rank bituminous coals in other parts of Wyoming and the world may contain minor amounts (less than 3%) of CO_2 and nitrogen (N_2), trace amounts of higher hydrocarbons (ethane, propane, butane, etc.), and sometimes traces of hydrogen sulfide (H_2S) (Rightmire, 1984; Kim, 1973).

As the coalification process begins, the plant detritus is first exposed to aerobic (oxygen utilizing) bacterial decay that depletes or metabolizes any free oxygen that remains in the source material and adds carbon dioxide. After the free oxygen is consumed (in fresh water environments such as formed the PRB coals), the first methane is formed as a respiration by-product of anaerobic (oxygen-free) bacteria. These specialized bacteria reduce the oxygen contained in the remaining hydrocarbons and release, as a waste product, methane and minor amounts of CO_2 (Rice and Claypool, 1981). This is the process known as biogenic methane formation.

If the coal is buried sufficiently deep to be thermally altered, a second phase of methane formation can occur (**Figure 6**). When the temperature rises above 122^o F, through increased burial depth or increased geothermal gradient, thermogenic processes on the coal begin and additional water, CO_2, and N_2 are generated. Maximum CO_2 generation, with little methane generation, occurs at about 210^o F. At about 250^o F, generation of methane exceeds generation of CO_2. Maximum thermogenic methane occurs from coal heated to approximately 300^o F (Rightmire, 1984).

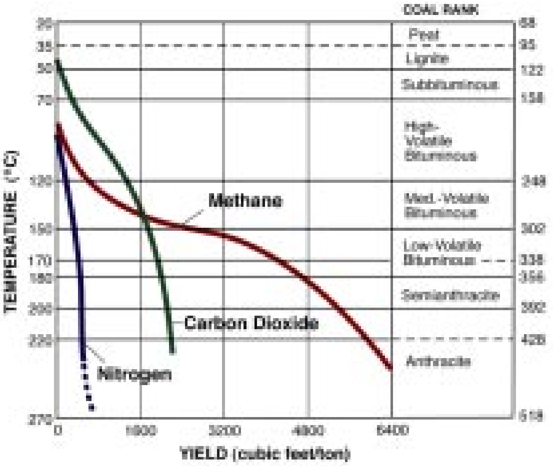

Figure 6. Calculated curves of gases generated by thermogenesis from coal during coalification (from De Bruin and others, 2000 as modified from Rightmire, 1984).

Over time, these thermal processes continue coalification, raising the coals in thermal maturity and rank (**Figure 6**) (Rightmire, 1984). The low rank of the PRB coals, coupled with the composition of the coal bed gases they contain, tell us that the methane contained in these coals is biogenic in nature. The Tertiary coal beds in the Wasatch and Fort Union formations exist in areas where individual beds can exceed 100 feet (or greater) in thickness and contain large amounts of coal bed methane, even though the gas yield per ton of coal is relatively low (De Bruin and others, 2000).

CBM well completion methods used in the PRB must be understood in order to assess the potential for self-heating and ignition of coals. In the Powder River Basin, coalbed methane wells are completed open-hole (**Figure 7**).

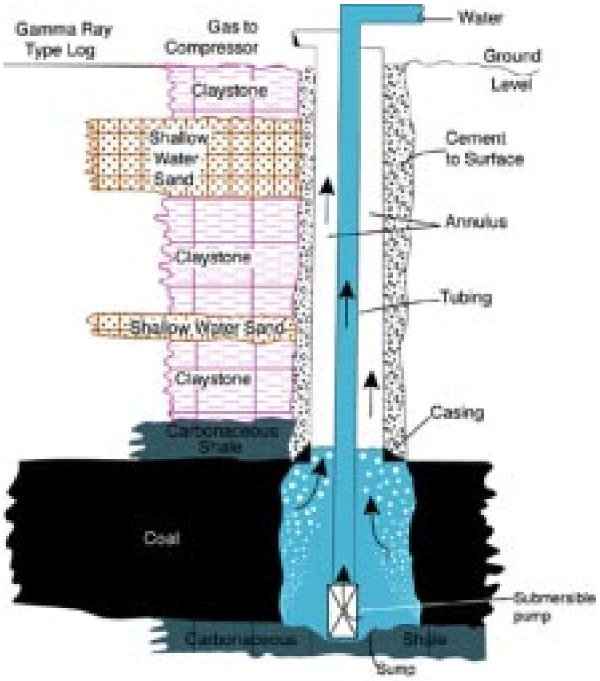

Figure 7. Schematic diagram showing open-hole completion technique for a typical PRB CBM well (De Bruin and others, 2000, as modified from diagram furnished by the Wyoming State Engineer's Office).

Using this completion method, casing is set to the top of the target coal bed and the underlying target coal zone is under-reamed and cleaned out with a fresh-water flush. A downhole submersible pump produces water up the tubing; gas released from the coalbed is produced up the annulus. Natural gas and water produced at individual wells are piped to a metering and gathering facility, where the amount water and gas from each well is recorded. The methane then flows to a compression facility, where the gas is compressed for pipeline shipment (De Bruin and others, 2000). The water may be disposed via surface release, impondment, or re-injection.

Occasionally a "blower" will be placed in-line at the gathering station. These blowers speed the flow of gas away from the well by slightly lowering the bottom hole pressure in the producing wells. A misconception held by some concerning blowers on CBM lines is that they suck air into the seam, when in fact they create a slight vacuum that speeds the de-gasification of the bed. Air is a contaminant of CBM production. While this production method is known as an open-hole completion, the well configuration is constructed to keep air out of the system.

SUMMARY

The preceding discussions indicate that conditions for the self-ignition of coal are not present in the immediate vicinity of coalbed methane wells of the Powder River Basin. The following is a review of those conditions that favor spontaneous combustion in subbituminous coals of the Powder River Basin and how the conditions relate to CBM exploration, well completion, and production.

- **Oxidation of coal.** Recall the simplified basic reaction for oxidation of coal: $\mathbf{C + O_2 = CO_2 + Heat.}$ First, oxygen is kept out of the CBM wells since it is a contaminant. Second, subsurface water from CBM wells has a redox potential (Eh-factor) that favors the reduction side of the reduction/oxidation reaction. Even where the coal has been completely dewatered, insufficient oxygen is present for oxidation to be carried forward. Any oxygen and heat generated would be quickly vented to the surface, before sufficient heat could result in coal ignition.

- **Heat of wetting.** This is only a problem in areas above the zone of saturation. In the vast majority of CBM wells, complete dewatering of the coal is not the objective. Only enough water is pumped to lower the hydrostatic pore pressure in the coal to allow for the desorption of the methane from the coal bed. However, even in the rare case of a well completely dewatering a seam, any heat generated from the heat of wetting or oxidation would be vented to the surface before it could build up enough to result in a coal ignition.
- **Airflow rate.** The airflow rate in a CBM well by design is very low to null, and in a direction directly out of the well. The flow out of the well provides no oxygen for the oxidation process and it efficiently dissipates any heat that has been generated. Recall the *in situ* UCG experiments discussed earlier, where forward coal ignitions were not sustainable even where millions of standard cubic feet of air were injected into the dewatered coal.
- **Particle size.** Particle size has an inverse relationship to spontaneous combustion in coal. The smaller the particle size, the greater surface area is available on which oxidation can take place. In surface coal mines, an appreciable amount of fine material must be present to favor spontaneous coal combustion (see above). The relatively small hole diameter of a CBM well prohibits large volumes of fines to accumulate. CBM operators flush the hole prior to production and setting their submersible pumps. Fines that do collect in the area of the pump require maintenance of the well to clean the hole of fines. In a dry hole, if heating occurs the operators can detect the wells producing contaminated gases and shut them in before the gases foul the collection system.
- **Rank.** The subbituminous-rank coals in the PRB contain a high percentage of reactive macerals (vitrinite and exinite) and therefore are candidates for spontaneous combustion. Coal ignition requires the factors listed above, but these factors appear to be absent in CBM wells.
- **Temperature.** The higher the temperature, the faster coal reacts with oxygen. Construction of CBM wells vents heat out of the coal so that temperatures needed for coal ignition are neither present nor anticipated to occur.
- **Pyrite content.** Generally pyrite or marcasite must be present in concentrations greater than 2% before it has a significant effect. Tertiary coals of the PRB are very low in the occurrence of these inorganic sulfide minerals.
- **Geological factors.** While rocks are poor conductors of heat, CBM wells are very efficient (in their design) in carrying heat away from the coal and venting it to the surface. Faults and fractures that may be present in the overburden are sealed via casing and cement to permit dropping the hydrostatic pressure in the coal bed for CBM production.

During the production phase of CBM activity, conditions necessary to foster spontaneous combustion of coal are not present. After the coal seam is depleted of economical methane resources, wells must be plugged and sealed. Unlike abandoned underground mines, CBM wells leave no underground voids susceptible to further subsidence and associated spontaneous coal ignition. The likelihood of completely dewatering a coal bed and exposing large areas of fine coal particles to oxygen seems extremely remote.

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