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Mechanism of instantaneous coal outbursts

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Notes

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ABSTRACT

Thousands of mine workers die every year from mining accidents, and instantaneous coal outbursts in underground coal mines are one of the major killers. Various models for these outbursts have been proposed, but the precise mechanism is still unknown. We hypothesize that the mechanism of coal outbursts is similar to magma fragmentation during explosive volcanic eruptions; i.e., it is caused by high gas pressure inside coal but low ambient pressure on it, breaking coal into pieces and releasing the high-pressure gas in a shock wave. Hence, coal outbursts may be regarded as another type of gas-driven eruption, in addition to explosive volcanic, lake, and possible ocean eruptions. We verify the hypothesis by experiments using a shock-tube apparatus. Knowing the mechanism of coal outbursts is the first step in developing prediction and mitigation measures. The new concept of gas-driven solid eruption is also important to a better understanding of salt-gas outbursts, rock-gas outbursts, and mud volcano eruptions.

INTRODUCTION

Instantaneous coal outbursts in underground coal mines are violent and spontaneous ejections of coal and gas from the working coalface. In the process, a large amount of coal and gas (CH_4 gas, CO_2 gas, or both) is expelled violently, and coal is pulverized. These violent outbursts are major disasters in coal mines. Coal outbursts are also referred to as coal mine outbursts (Beamish and Crosdale, 1998), gas outbursts (Hyman, 1987; Aguado and Nicieza, 2007), coal and gas outbursts (Hargraves, 1983; Yu, 1985), or gas and coal outbursts (Bodziony and Lama, 1996). Coal outbursts are related to but different from two other types of mining disasters. (1) Coal or rock bursts are collapses without the release of a significant amount of gas and are related to high stress in coal or rock. In the eastern United States and Canada, bursts are referred to as bumps (Campoli et al., 1987; Iannacchione and Zelanko, 1995), but sometimes coal outbursts may also be referred to as bumps or gas-driven bumps (Iannacchione and Zelanko, 1995). (2) Methane gas explosions are spontaneous and explosive combustion of methane due to high concentration of methane in air. Nonetheless, outbursts can lead to methane explosions. For example, on 20 October 2004, a coal outburst led to a methane explosion in Daping coal mine (Henan Province, China), killing 148 miners (http://www.ha.xinhuanet.com/xhzt/tfsj/index.htm). On 15 April 1981, a coal outburst at Dutch Creek No. 1 Mine (Colorado, United States) caused an explosion, killing 15 workers (http://www.usmra.com/disasters_80on.htm). This work focuses on instantaneous underground coal mine outbursts.

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The first recorded coal outburst occurred in France on 22 March 1834 (Wang and Yu, 2005); there were two fatalities. Since then, frequent coal outbursts have killed numerous miners worldwide; Table DR1 in the GSA Data Repository[1] lists some deadly outbursts. Coal outbursts have occurred in at least 18 nations (Bodziony and Lama, 1996), notably China, Russia, Turkey, Poland, Belgium, and Japan. They occur in deep mines ranging from 80 m depth to the deepest, ~1150 m depth (Lama and Bodziony, 1998). As deeper coals are mined, the likelihood of coal outbursts increases. In recent years, with the rapid economic development of China, frequent coal outbursts have brought much suffering to the Chinese mining community.

Scientists have investigated the mechanism of coal outbursts since 1852. Bodziony and Lama (1996) comprehensively reviewed literature in English, Russian, German, and Polish languages. More recent progresses and reviews can be found in Jiang and Yu (1998), Lama and Bodziony (1998), Cao et al. (2001), Wang and Yu (2005), Xu et al. (2006), and Aguado and Nicieza (2007). Most existing models fall into three categories: the pocket model, the dynamic model, and the multiple-factor model (Bodziony and Lama, 1996). The pocket model advocates that weak and gas-rich pockets of coal (crushed coal or more fractured coal) are enclosed by gas-poor and less fractured coal. In the context of this model, when these weak and gas-rich pockets are encountered in mining, an outburst can occur. However, even though it is partially correct because there are indeed weaker parts in highly inhomogeneous coal, this model cannot account for, among other observations, why coal outbursts occur most often when a new seam of coal is exposed, because excavation to open a new seam should not preferentially encounter weak and gas-rich pockets. The dynamic model suggests that normal gas-rich coal is weakened by mining-induced fractures ahead of an advancing face in coal, and is hence outburst prone. This model does not account for the major role of gas in coal outbursts, and may apply better to bursts (without gas involvement) due to rapid decompression from a high strain state. The multiple-factor model (Hargraves, 1983; Bodziony and Lama, 1996) states that outbursts are the results of several factors (such as gas content, rock pressure, tectonic environment, excavation, and gravity; or stress, strength, and gas) acting together. Even though these factors indeed play a role, it is necessary to see through the complicated factors to gain a deeper insight. Jiang and Yu (1998) developed a spherical shell failure model. Each of the models captures some important aspects of the process, but none gives the complete picture. Furthermore, none of the models has been successful in developing quantitative measures to predict and prevent coal outbursts. Thus, empirical measures to predict outburst conditions vary from one region to another (Lama and Bodziony, 1998). In short, despite extensive studies and numerous models over more than 150 years, the fundamental mechanism of coal outbursts remains unknown (Bodziony and Lama, 1996; Beamish and Crosdale, 1998; Wang and Yu, 2005; Aguado and Nicieza, 2007), and coal outbursts continue to be a major threat to underground mine workers.

[1]GSA Data Repository item 2009229, experimental apparatus (Figure DR1) and procedures, Table DR1 (deadly coal outbursts in the last 130 years), Figure DR2 (six continuous frames of outburst experiment 102), Video DR1 (video clip of experiment 5) and Video DR2 (video clip of experiment 102), is available online at www.geosociety.org/pubs/ft2009.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

HYPOTHESIS

We hypothesize that the mechanism of coal outbursts is similar to that of magma fragmentation and the ensuing explosive volcanic eruption. Explosive volcanic eruptions and magma fragmentation have been investigated extensively (McBirney and Murase, 1970; Sparks, 1978; Wilson et al., 1980; Alidibirov, 1994; Papale, 1999; Zhang, 1999; Liu and Zhang, 2000; Spieler et al., 2004; Zhang et al., 2007), and the mechanism is explained here for reference. Before an explosive eruption, the magma contains a high concentration of dissolved gas. The gas component is mainly H_2O, which is a gas at magmatic temperatures. Under high pressures, magma can dissolve a high concentration of H_2O (~6 wt% at 200 MPa; e.g., Liu et al., 2005). As pressure on magma is reduced (e.g., due to sudden removal of overlying rocks as in the case of 1980 eruption of Mount St. Helens, or due to ascent of magma), gas bubbles grow rapidly, leading to volume expansion of the gas-magma system, which forces the magma to erupt. Further ascent of magma reduces the ambient pressure even more in a runaway process. The high pressure in bubbles and low ambient pressure on the magma lead to high tensile stress along bubble walls. When the tensile stress exceeds the tensile strength of magma, magma fragments into pieces, leading to an explosive eruption. That is, fragmentation is a defining moment of a volcanic eruption: before fragmentation it is nonexplosive, and after fragmentation it is explosive.

In our hypothesis on the mechanism of coal outbursts by analogy to magma fragmentation, in coal beds, CH_4 and/or CO_2 are dissolved or absorbed in coal. Under high pressures, coal can hold a large amount of gas (e.g., Cui et al., 2007) and hence there may or may not be a free gas phase in cracks (including joints) and pores, depending on the ambient pressure and gas content. Excavation in the process of mining reduces the pressure on coal. If there is initially gas in cracks and pores, they grow. If there is no initial gas, as the ambient pressure is reduced to below the partial gas pressure corresponding to the gas content in coal, gas becomes supersaturated and some gas desorbs and/or exsolves into cracks and pores in coal. The cracks and pores grow as pressure is further reduced. The difference between the high pressure in cracks and pores and the low pressure on coal results in tensile stress along cracks and pores. At some point, often when a coal bed is open because sudden decompression to the minimum confining pressure occurs at this time, the tensile stress exceeds the tensile strength of coal and high gas pressure fragments coal, releasing high-pressure gas that suddenly decompresses, leading to a shock gas wave carrying fragmented coal pieces into the open space, which is a coal outburst. Hence, in the context of our hypothesis, coal outbursts depend on the strength of coal (emphasized by the pocket model), gas content in coal (also emphasized by the pocket model), and the stress on coal (emphasized by the dynamic model). In addition, gas content, rock pressure, tectonic environment, excavation, and gravity affect the stress on coal, and they all play a role in reaching the condition of stress exceeding strength in the occurrences of coal outburst, as suggested by the multiple-factor model. In the context of our conjecture, for a given type of coal and a given depth, whether there would be an outburst is determined by one single condition: whether the internal gas pressure exceeds a threshold pressure (equivalent to a threshold stress) (Spieler et al., 2004). Coal outbursts may be regarded as another type of gas-driven eruption, in addition to explosive volcanic eruptions carrying magma particles (Wilson et al., 1980), lake eruptions carrying water droplets (Kling et al., 1987; Sigurdsson et al., 1987; Zhang, 1996; Zhang and Kling, 2006), and possible ocean eruptions (Zhang, 2001, 2003; Ryskin, 2003; Zhang and Xu, 2003; Zhang and Kling, 2006).

EXPERIMENTAL APPROACH AND RESULTS

In order to test our hypothesis, we developed an experimental program to investigate the fundamental mechanism of coal outbursts using experimental approaches for explosive volcanic eruptions (Kieffer and Sturtevant, 1984; Zhang et al., 1992, 1997; Mader et al., 1994, 1997; Spieler et al., 2004). A shock-tube apparatus was built at Peking University (Fig. DR1 in the Data Repository) to simulate the sudden decompression of coal samples, similar to those used in previous studies of volcanic eruptions. We used a coal-CO_2 system in our experimental simulation instead of a coal-CH_4 system because there are CO_2-driven coal outbursts (Table DR1) and because CO_2 is safer than CH_4. Details about the experimental apparatus and procedures can be found in the GSA Data Repository. To quantitatively measure the degree of fragmentation (F) after an experiment, we define:

$$F = \frac{M_0 - M_1}{M_0}, \tag{1}$$

where M_0 is the initial mass of the coal cylinder, and M_1 is the mass of the largest remaining coal piece after the experiment.

The most important result of this study is that for coal pressurized in CO_2 at high pressure for some long duration, sudden decompression often leads to significant coal fragmentation. Figure 1 shows recorded video frames of an experiment (exp 5) pressurized to 1.9 MPa and then decompressed: the top part of the sample fragmented at frame C. Video frames for another experiment (Fig. DR2) and video clips for these two experiments can be found in the GSA Data Repository. These and other experiments show that high gas pressure

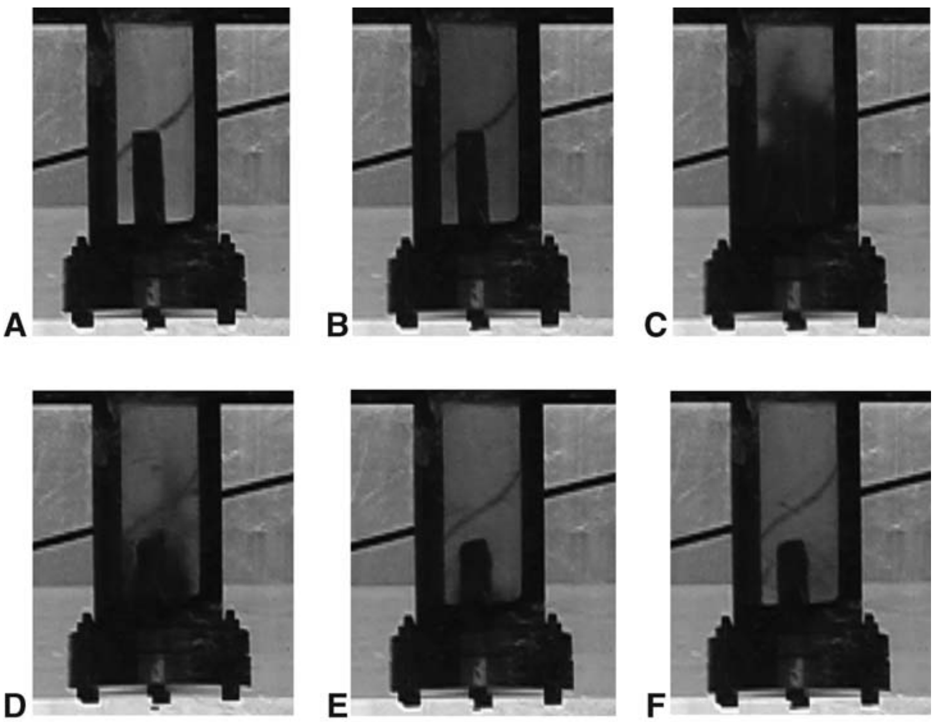

Figure 1. Six continuous frames of video camera recording (representing 0.2 s) of an experiment on Dashucun coal (exp 5). The initial length and diameter of the coal cylinder are 90 mm and 16 mm, respectively. Coal fragmentation occurs in frame C. Before sudden decompression shown in this figure, coal sample was pressurized by CO_2 at 1.9 MPa for 89 hours. Degree of fragmentation is 21.5%. Thick line behind test cell is copper tubing (connecting test cell to vacuum pump). Video clips for this experiment and another experiment can be seen in GSA Data Repository (see footnote 1).

in coal can lead to fragmentation, consistent with our hypothesis that coal fragmentation is a type of gas-driven eruption. In order to verify that gas inside coal powers an outburst, we carried out zero-time experiments (bringing up to pressure and decompressing immediately, without allowing time for gas to diffuse into coal). No outburst occurred.

The second result is that even though high CO_2 pressure does lead to coal fragmentation, there is no single threshold pressure for fragmentation to occur. The threshold depends on the type of coal and can be variable even for the same type of coal. Our experiments using anthracite coal from the Mengtougou coal mine in the suburbs of Beijing show that it maintained its shape when decompressed from 1.8 and 3.0 MPa, but was pulverized when decompressed from 3.2 MPa. In terms of the degree of fragmentation (F) defined by Equation 1, at 1.8 and 3.0 MPa, F is <0.004, whereas at 3.2 MPa, F = 0.827 (Fig. 2A). Experiments using bituminous coal from Fengfeng Mine Field (including Dashucun mine, where an outburst on 19 April 2007 killed 17 people, and its neighboring mine Wutongzhuang), on the other hand, show more scatters: three cylinders partially fragmented at 1.9 MPa, 2.8 MPa, and 3.0 MPa after pressurization for sufficient time; but three others did not fragment at all at 2.0 MPa, 2.5 MPa, and even at 3.0 MPa (Fig. 2B); two of these (2.5 MPa, and 3.0 MPa) are

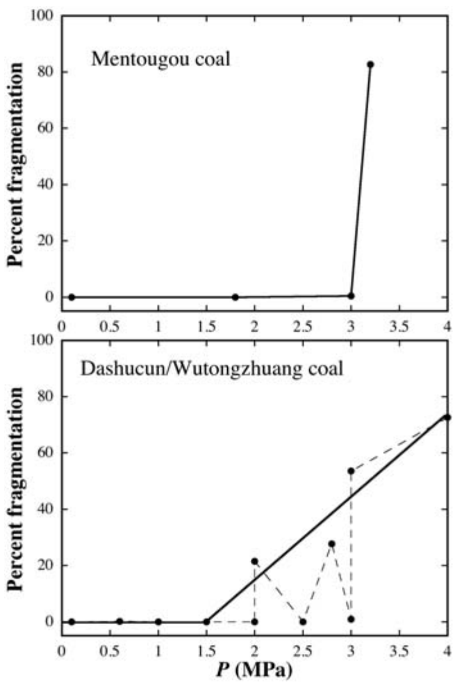

Figure 2. Percentage of fragmentation versus test cell pressure for two types of coal. Points are data and are connected. In lower diagram, two straight segments are drawn through scattered data as guides.

for cylinders with smaller radius. At 4.0 MPa, the fragmentation is almost complete (Fig. 2B; Fig. DR2). The variability of the fragmentation threshold is attributed to heterogeneity of coal samples. Furthermore, small coal cylinders used in our experiments are expected to have greater strength than coal seams in mines, based on the scale-dependence of rock strength (Adey and Pusch, 1999).

DISCUSSION

More comparisons can be made between volcanic eruptions and coal outbursts. (1) Similar to the variety of volcanic eruptions ranging from explosive, semi-explosive, and non-explosive (magma flow), to gradual degassing without eruption, coal eruptions also display such varieties with different explosivity, ranging from the most explosive (instantaneous outbursts involving both coal and gas) to less explosive (coal collapse without gas involvement) to gradual degassing without much coal collapse. (2) If the permeability of the overlying rock is very low, oversaturated free gas may be trapped in cracks and pores of coal (similar to bubbly magma at the top of a magma chamber), leading to outburst-prone coal as well as an extreme gas/coal volume ratio in some outbursts. (3) Similar to the dependence of the magma fragmentation threshold on the vesicularity (Spieler et al., 2004), the coal outburst threshold (or coal strength) is expected to depend on crack abundance and distribution in coal (Bodziony and Lama, 1996). In fact, coal properties are much more heterogeneous than magma properties, and hence the outburst threshold is much more difficult to quantify.

Major differences exist between volcanic eruptions and coal outbursts. (1) Magma is a fluid and so bubbles in magma can grow and expand almost freely; however, coal is solid and so cracks and pores in coal cannot expand freely. (2) In an explosive volcanic eruption, bubbles play the critical role, whereas in coal outbursts, it is expected that cracks rather than pores play the dominant role because stress concentrates at crack tips instead of roughly spherical pores. (3) Melt is isotropic and roughly homogeneous, whereas coal is anisotropic and highly heterogeneous in terms of strength and crack and/or bubble distribution. Many factors may affect the strength (Bodziony and Lama, 1996; Aziz and Ming-Li, 1999). These differences mean that coal outburst thresholds can be highly variable and therefore are more difficult to quantify than the magma fragmentation threshold.

Coal outbursts require sufficient gas pressure. Internal gas pressure in coal is usually limited by the local hydrostatic or lithostatic pressure. Thus, coal outbursts only occur at depth because great depth is necessary for high gas content. As deeper coal is mined, higher gas pressure is possible, and hence it is more likely to have coal outbursts. Nonetheless, greater depth does not necessarily mean high gas pressure, and the correspondence between depth and likelihood of outbursts is not one to one. Structures that help maintain and/or concentrate gas or reduce coal strength would lead to more outbursts as well as more violent outbursts.

The new concept of gas-driven solid eruptions that we proposed is more general than coal outbursts and can be extended to porous and gas-rich salt, sandstones, and mudstones initially under high gas pressure: they may also erupt (outburst) when suddenly decompressed. Such eruptions may occur in sediments as mud volcanoes (Milkov, 2000), or in mines as salt and gas outbursts (Lama and Bodziony, 1998) or rock and gas outbursts (Hyman, 1987; Aston et al., 1990; Barron and Kullmann, 1990). On the other hand, coal and rock may also collapse under sufficient stress in a burst without gas involvement, just as there are also nonexplosive (non-gas-driven) volcanic eruptions.

CONCLUSIONS

Our conjecture that coal outbursts are due to high gas pressure in coal through a mechanism similar to magma fragmentation is verified by experiments. Therefore, coal outbursts can now join the expanding list of gas-driven explosive eruptions, i.e., volcanic, lake, and possible ocean eruptions. Theories developed for the dynamics of volcanic eruptions (e.g., Fink and Kieffer, 1993) may be applied to investigate coal outburst dynamics. The conditions for coal outbursts can be quantified using the outburst threshold, which may be sharp but more likely spans a range of pressures for a given coal seam due to coal heterogeneity. Our conjecture may eventually lead to prediction of coal outbursts.

Knowing the mechanism of coal outbursts is the critical first step in preventing such disasters. Future developments include further verification of the hypothesis, visualization of the coal outburst process in detail by recording experiments with a high-speed camera, and determination of outburst thresholds as a function of the type of coal (such as crack density, porosity, and coal metamorphic grade) and the kind of gas (CO_2, CH_4, or mixtures). To achieve the goal of predicting and preventing coal outbursts in deep coal mines, it is best to determine the gas pressure in situ in a given coal mine (which is possible already) and the range of outburst threshold in situ in the coal mine. If the gas pressure in the coal bed exceeds the lower limit of the threshold range (or a fraction of the lower limit because a safety factor is needed), the coal must be degassed before mining to avoid coal outbursts. Much more scientific and engineering work will be needed to prevent coal outbursts in underground coal mines.

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Mechanism of instantaneous coal outbursts—Supplementary materials

GSA Data Repository item 2009229

This supplementary data repository includes the following:
1. Table DR1 lists some deadly coal outbursts in the last 130 years.
2. Experimental apparatus and procedures.
3. Figure DR2 shows six continuous frames of outburst exp 102.
4. Two video clips, one for exp 5 (Figure 1) and one for exp 102 (Figure DR2).

1. Table DR1

TABLE DR1. SOME DEADLY COAL OUTBURSTS IN THE LAST 130 YEARS

Year	Country	Mine	Outburst coal (ton)	Outburst gas (m^3) F	atalities	Ref.
1879	Belgium	Agrappe	–	–	141	1
1930	Poland	Wencelaus	5000	28,000 CO_2 151		1
1941	Poland	Nowa Ruda			187	2
1958	Canada	Springhill	–	–	74	a
1960	China	Songzao #2, Chongqing	1000	–	125	3
1978	China	Yaojie #3, Gansu	1030	240,000 CO_2 90		3
1981	Japan	Yubari-Shin	6500	600,000 CH_4 93		1
1985	China	Meitian #3, Guangdong	3200	720,000 CH_4 56		3
1992	Turkey	Kozlu	–	–	263	1
2007.04.19	China	Dashucun	1200	–	17	b
2007.05.24	Russia	Yubileynaya	–	–	35	c
2008.05.23	Ukraine	Donetsk	–	–	8*	d
2008.07.31	China	Zigui, Hubei	–	–	6	e

References: 1—Beamish and Crosdale, 1998; 2—Lama and Bodziony, 1998; 3—Wang and Li, 2002; a—http://www.gov. ns.ca/nsarm/virtual/meninmines/disasters.asp?Language=English; b—http://www.yzsafety.gov.cn/neirong.php? newsid=2229; c—http://www.regnum.ru/english/832640.html; d—http://mns.gov.ua/daily/showdailyarchive.php?day =1&month=6&year=2008&l=en; e—http://news.xinhuanet.com/newscenter/2008-08/04/content_8953817.htm.

*Three were missing in addition to the eight deaths.

More complete summaries of outburst occurrences can be found in Bodziony and Lama (1996), Beamish and Crosdale (1998), and Wang and Li (2002).

2. Experimental Apparatus and Procedures

The apparatus (Fig. DR1) consists of mainly a Lexan (polycarbonate) test cell and a large tank above it. The test cell is 50 mm in diameter and either 400 or 200 mm long. Thin-wall test cells (3 mm thick) were used in earlier experiments and they rupture at ~3.2 MPa. A customer-fabricated thick-wall (10 mm thick) test cell was used in later experiments to reach higher pressures. At 4 MPa, the solubility of CO_2 in coal is ~5 wt% (Cui et al., 2007). This is a very high concentration of gas. (In comparison, for explosive volcanic eruptions, the pre-eruptive H_2O content in magma is often 4-7 wt%.) The base of the test cell is made of steel. Above the test cell is a large cubic tank (~1 m on each side). Inside the tank, there is an electromagnetically driven knife. The test cell is separated from the large tank by layers of aluminum foil (the number of layers of aluminum foil depends on the test cell pressure), which can be cut by electromagnetically driven knife blades inside the tank.

Figure DR1. Experimental apparatus for coal outbursts. A coal cylinder is inside the test cell.

The starting coal samples were large chunks of coal we collected from coal mines. Long cuboids were cut from the chunks and then were ground to quasi-cylinders of 10–20 mm in diameter and ~0.1 m long.

In an experiment, the base of the coal cylinder was glued to the base of the test cell, which was then connected to the large tank. The cell was evacuated to remove air. Then CO_2 was let into the test cell at a desired high pressure (such as 2.5 MPa). The test cell was maintained at high CO_2 pressure for a couple of days to allow CO_2 diffusion into coal and reach rough equilibrium. The duration at high CO_2 pressure was estimated from $t = r^2/D$ where t is time, r is the radius of the coal cylinder and D is CO_2 diffusivity in coal (Saghafi et al., 2007). To achieve sudden decompression, the knife in the tank was triggered to come down to cut open the aluminum foil. The high gas pressure in the test cell then completely opened the aluminum foil, leading to a loud noise similar to gunshot sound. (Sometimes, only a tiny hole was open in the aluminum foil, leading to slow decompression. These experiments were not counted.) Most experiments were recorded by a video camera. Observation was made on whether the coal sample stayed as one piece or fragmented into pieces.

3. Video Frames for Experiment 102

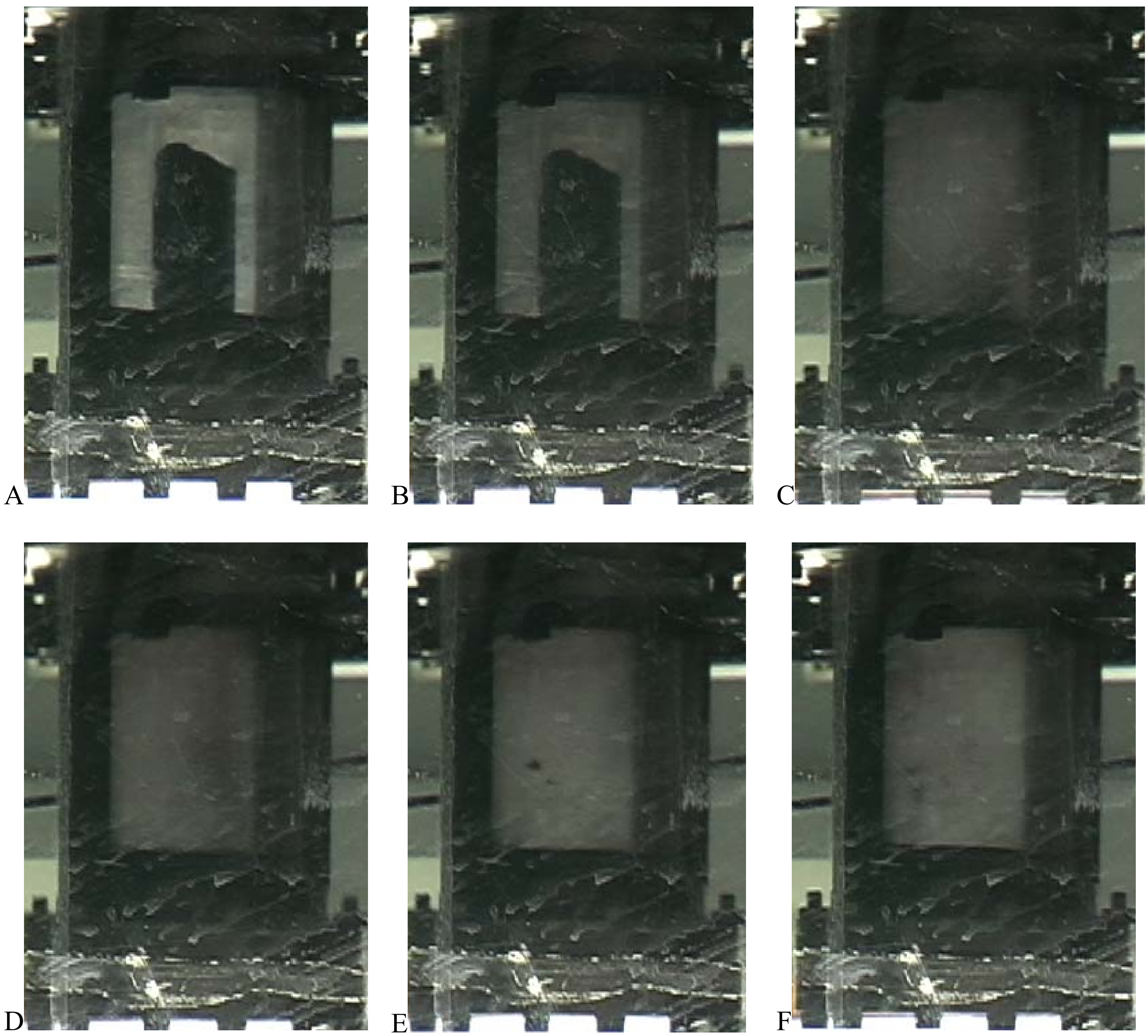

Figure DR2. Six continuous frames of video camera recording (representing 0.2 s) of outburst experiment 102. Coal fragmentation occurred between frame B and C (that is, in less than 0.033 s). Before sudden decompression shown in this figure, the coal sample was pressurized in CO_2 at 4.0 MPa for 2.9 days. After the experiment, degree of fragmentation is 72.6%. The QuickTime movie can be seen by clicking the link Experiment 102 below.

4. Video Clips for two Experiments

Video DR1: Experiment 5

Video DR2: Experiment 102

References Cited in This Supplement:

Cui, X., Bustin, R.M., and Chikatamarla, L., 2007, Adsorption-induced coal swelling and stress: implications for methane production and acid gas sequestration into coal seams: J. Geophys. Res., v. 112, p. doi: 10.1029/2004JB003482.

Saghafi, A., Faiz, M., and Roberts, D., 2007, CO_2 storage and gas diffusivity properties of coals from Sydney Basin, Australia: International Journal of Coal Geology, v. 70, p. 240–254, doi: 10.1016/j.coal.2006.03.006.

Wang, J.F., and Li, W.J., 2002, Collection of Reports and Comments on Coal Mine Accidents in China: Beijing, Coal Industry Press (in Chinese), 3032 p.