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Is there a potential of emission of sequestered CO_2 from Illinois bituminous coal under shockwaves?

Samuel Harbin, Nickolas J. Twombly, Richard D. West, Vivak M. Malhotra *

Southern Illinois University-Carbondale, Department of Physics, Carbondale, IL 62901-4401, USA

HIGHLIGHTS

- Probed how shockwaves may affect the sequestered CO_2 in bituminous coal.
- Fabricated a system to apply shockwaves to cores while monitoring emitted gases.
- Shockwaves did not induce gas emission from non-pressurized coal cores.
- Massive amounts of CO_2 emitted from coal cores under compressive shock.
- Shocks ejected almost all the CO_2 from pressurized coal in less than 1 h.

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ABSTRACT

The mitigation of potential global warming due to the emission of greenhouse gases, especially CO_2, would require large-scale geological sequestration. Though current emphasis has been on identifying and characterizing the potential geological sequestration reservoirs, there is also an urgent need to ensure that the sequestered CO_2 will remain in place under reasonable perturbations, e.g., under seismic activity. One of the potential geological reservoirs identified is unmineable coal seams due to the advantage of recovering fuel gas like CH_4 while sequestering CO_2. Therefore, a closed experimental setup was constructed where Illinois bituminous coal cores could be subjected to compressive shockwaves while simultaneously monitoring the emission of gases from CO_2 pressurized coal cores. The results from the pressurized coal cores were compared with the behavior manifested by un-pressurized coal cores as well as porous pumice stone cores, which were also subjected to shockwaves. As expected, the un-pressurized cores showed no significant emission of CO_2 when subjected to shock; however, this was not the case for the cores which were pressurized with CO_2. The results indicate that massive amounts of CO_2 would be emitted if the cores were exposed to atmospheric pressure simulating a situation where caprock has been compromised during primary seismic activity. Irrespective of the belief that coal interacts strongly with CO_2, both chemically and physically, compressive (0.374 MPa) shockwaves forced almost all the CO_2 to be ejected from the coal cores. Surprisingly, most, if not all, the sequestered CO_2 would be emitted in less than 1 h if the cores were subjected to reasonably moderate shocks. In actual seismic activity conditions, one expects conditions to be even more severe than in the experimental setup used in this study because of the presence of compressive and transverse stresses and shears. If such is the case, CO_2 may be emitted even faster. It is reasonable to argue that Illinois bituminous coals may not be suitable hosts for sequestering CO_2 because the region is prone to seismic activity.

1. Introduction

The environmental concerns associated with carbon dioxide (CO_2) production when fossil fuels are combusted are coming to the fore because of potential global warming. The ensuing warming could affect the food production of the world as well as may intensify deleterious weather events. Because of these reasons, a considerable research effort is being undertaken in the USA, as well

Abbreviations: FTIR, Fourier transform infrared; MPa, mega Pascal; GPa, giga Pascal; M, moment magnitude; cm^{-1}, wavenumber; MCT, mercury cadmium telluride.

* Corresponding author. Tel.: +1 618 453 2643; fax: +1 618 453 1056.
E-mail address: vmalhotra@physics.siu.edu (V.M. Malhotra).

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as in Europe, toward economically separating CO_2 from flue gas, capturing it, and then developing strategies for long-term storage of the captured gas. Though at present separating and capturing CO_2 from the flue gas is expensive and needs further research, the long-term storage of the greenhouse gas, which the public perceives to be safe, must also be evaluated. The United States Department of Energy has developed a roadmap for potentially storing CO_2 in various mediums [1,2]. It is generally agreed that sequestering CO_2 in geological formations holds the most promise for the large-scale storage of the greenhouse gas.

A number of geological reservoirs have been identified [1–3], such as deep sandstone formations, shale reservoirs, and unmineable coal seams, for sequestering captured CO_2 produced by fossil fuel burning power plants. Though there is a considerable body of data available, which deals with injecting supercritical CO_2 in various reservoirs including adsorption and absorption characteristics, very little is known at present about how the sequestered CO_2 would behave under external perturbations [1–5]. Among the geological storage reservoirs, long-term immobilization of CO_2 in unmineable coal seams presents an added advantage of coal bed methane recovery while simultaneously sequestering CO_2. However, successful sequestration projects will only be feasible if the public perceives it to be safe and environmentally friendly.

Recently researchers [6–9] have cautioned about large scale CO_2 sequestration in geological reservoirs because of the potential of induced seismicity. The amount of CO_2 to be sequestered is gigantic. Zoback and Gorelick [7] point out that the United States produces about 2.1 billion metric tons per year of CO_2 from coal burning, while China generated almost 6.3 billion metric tons of CO_2 from coal combustion in 2011 alone. These authors argued “that there is a high probability that earthquakes will be triggered by injection of large volume of CO_2 into the brittle rocks commonly found in continental interiors”. Zoback and Gorelick point out that high pressure fluid injection results in increased pore pressure which in turn reduces frictional resistance to fault slippage, potentially triggering earthquakes. However, the problem could be further compounded if there are unmapped faults near the vicinity of the injection wells. Mazzoldi et al. [8] raise concerns that the induced seismicity “may provide preferential pathways for CO_2 leakage out of the reservoirs”.

It is also known that earthquakes have long range effects, e.g., after the 26th December 2004 earthquake in Sumatra, the Rayleigh waves swept across Alaska approximately 11,000 km (~6831 miles) distance and initiated “an 11-min swarm of 14 local earthquakes” [10]. West et al. [10] pointed out that surface waves from the Sumatra earthquake (moment magnitude, $M = 9$) created vertical trough-to-peak ground displacement of 1.5 cm in Alaska. West et al. also argued that shear and normal stresses work in tandem to promote faulting. Because, “Shear stresses alter the forces acting along fault planes, whereas normal stresses alter the confining pressure and friction across the fault” [10], the possibility of transient, though short-lived extreme local temperatures, cannot be discounted. The potential temperature rise along with rapidly varying pressure can have a serious consequence for both absorbed and adsorbed CO_2 in organic rocks like coal.

Our recent research efforts [11,12] have been directed toward evaluating the potential risks which may be associated with sequestering CO_2 in Midwestern coal seams and shale formations. The flexural strength and flexural modulus measurements on Illinois bituminous coal [11] suggested that there is a considerable strength and modulus heterogeneity in the coal samples which were free of visible defects. The strength of strips derived from a single chunk of coal showed strength variations from 2.8 MPa to 11.2 MPa, while modulus variations were 0.7GPa to 3.4GPa. These heterogeneities may be the source of defects and faults generation during even mild induced seismic activity. The other concern that was dealt with was whether Illinois bituminous coal showed glass transition. If Illinois coals do manifest glass transition close to the reservoir temperature, then there is a potential of reservoir instability during injection of high pressure CO_2, as it is known that CO_2 acts as a plasticizer and lowers the glass transition temperature. However, thermal, thermo-mechanical, and vibrational measurements indicated no glass transition for the Illinois bituminous coal at $30\,°C \leqslant T \leqslant 300\,°C$. Furthermore, because the Illinois basin is prone to high magnitude ($5.5 \leqslant M \leqslant 7.5$) earthquakes, it is important to understand how shockwaves affect the CO_2 stored in organic rocks like coal. The seismic activity may come from manmade or natural geological events. As pointed out earlier, there is a considerable body of data available on the adsorption and controlled desorption of CO_2 from coal [2], but practically nothing is known about how CO_2 pressurized coals behave when subjected to shockwaves. This paper reports how CO_2, which was sequestered in Illinois bituminous coal, behaved when the samples were exposed to shockwaves.

2. Materials and methods

2.1. Illinois bituminous coal core

For the present study, Herrin bituminous coal from the Cottage Grove mine was chosen and was procured from east of Harrisburg (just inside Gallatin County), Illinois, USA. The proximate and ultimate analyses of Cottage Grove mine coal have been reported in the literature [13]. The coal samples were first obtained in large chunks. These coal chunks were cut into thick sheets with the help of a diamond band saw. From these sheets, 4 cm circular coal cores were drilled out, using a drill press with diamond coring bit chucks. The drilled coal cores were vacuum dried at 25.4 cm of Hg at 50 °C in a heated vacuum desiccator for 24 h. After mildly vacuum drying, the bituminous coal cores were stored under atmospheric conditions prior to subjecting them to high pressure CO_2 injection. For comparison purposes, porous pumice stone was also obtained and 4 cm circular stone cores were machined in a manner similar to coal cores. A belt sander was used to make the samples relatively flat on both ends of the cylindrical cores, if needed, so that the maximum surface contact would occur with the plunger during shockwave experiments.

2.2. Shockwave setup

As pointed out earlier, no experimental studies are available in the literature where researchers have explored how seismic activity may affect the behavior of adsorption/desorption of sequestered CO_2 in geological formations. To answer some of the questions related to how seismic activity may affect the reemission characteristics of sequestered CO_2, a closed, high pressure cell system was designed and built. In the cell system, cylindrical coal cores could be subjected to shockwaves while simultaneously studying the emission behavior of sequestered gases and/or vapors from the coal cores. Figs. 1 and 2 show the block diagram and photographs of the overall system, respectively. The main features of the shockwave system are:

- Application of the shockwaves: A number of cylindrical iron rods of various lengths were machined from a 1.3 m iron bar stock rod. These rods were calibrated for weight and were used to apply shockwave to coal cores by dropping the rods from well-defined heights. To ensure the iron rods would strike the center of the piston, the iron rods were dropped from the top of rigid, transparent Plexiglas tubes. Heights of the tubes were varied as needed, with heights of 0.31 m, 0.61 m, 1.22 m, and

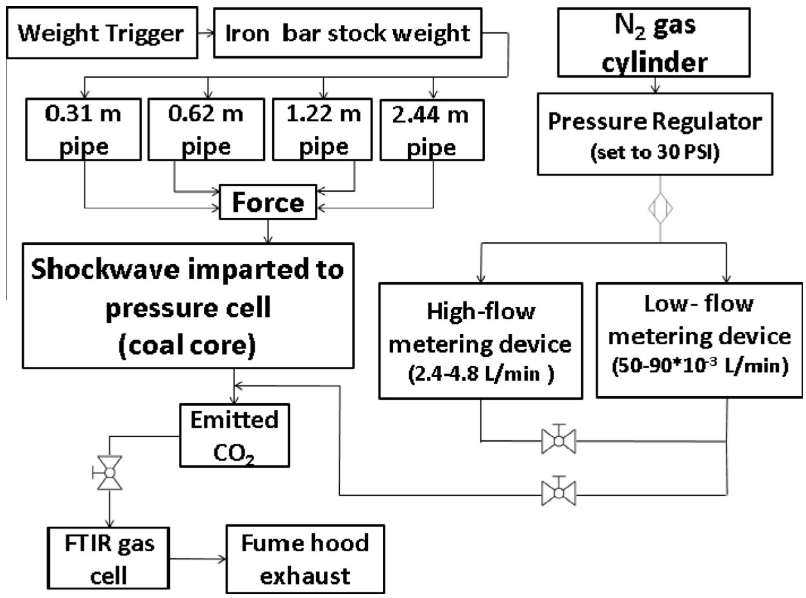

Fig. 1. The schematic of the high-pressure cell system for imparting shockwaves to cylindrical cores of diameter 2.54 cm and 4 cm.

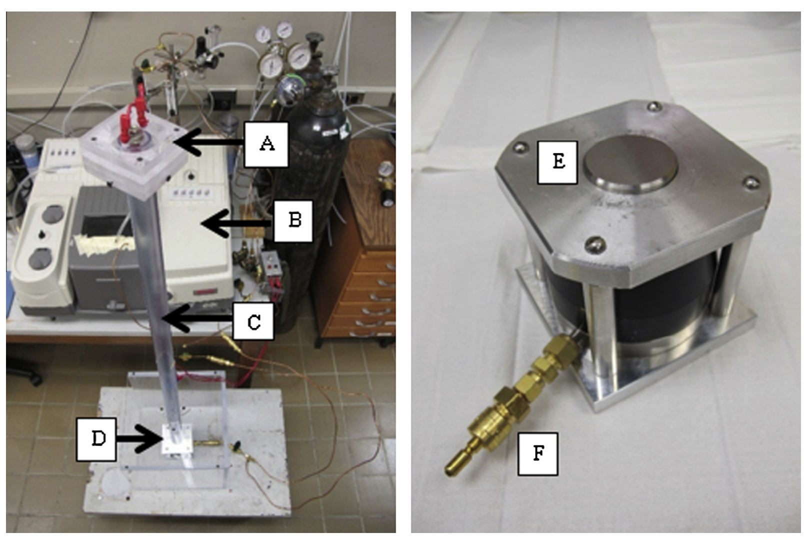

Fig. 2. Photographs of the high pressure cell system for subjecting the coal cores to shockwaves. A: Electromagnetic trigger, B: FTIR spectrometer, C: Plexiglas guide tube, D: High-pressure die, E: 4 cm piston, and F: High-pressure fittings.

2.44 m possible for the weight drop experiments. Holes were drilled into the tubes at the lower end. This was done to allow air to flow easily out of the tubes and minimize the drag on the falling weight, as well as to hold a safety catch to prevent a premature impact. Prior to the drop, the iron rods were held at the top of the Plexiglas tube by an electromagnet. The impulse on the piston was determined by calculating the final velocity of the iron rod. The approximate time of contact between the iron rod and the piston was determined with the help of a high speed camera. This allowed us to calculate the impact force on the piston, thus, the applied shock pressure to the sample cores.

- High pressure die: The coal cores were housed in a 4 cm diameter modified high-pressure die (see Fig. 2) with a piston, made from hardened stainless steel, which could compress or transfer shock to the samples when impacted. The die had O-rings both at the bottom and at the top to ensure that no gases escaped from the die during the shockwave experiments. The design of the die is such that during compression or shockwave experiments, the emitted gases were driven to the high-pressure fittings at the bottom of the die.
- Monitoring of emitted CO_2: The high pressure die is coupled to an optical high pressure gas cell, shown in Fig. 3, mounted inside a fast scanning Fourier transform infrared (FTIR) spectrometer (Nicolet 6800). The gas cell was fitted with well-polished KBr windows. The infrared beam is passed through the cell. The beam then strikes the fast response, liquid nitrogen cooled MCT detector of the spectrometer. As the hardened stainless steel piston applied a transient pressure to the coal cores in the die, the emitted gases were driven to the gas cell by injecting N_2 gas to the high pressure line just as the gases were being ejected from the high pressure die. Because N_2 gas has no vibrational modes in the frequency range 4000–400 cm^{-1}, only the CO_2 bands will be observed in the arrangement. It is possible to observe other emitted vapors, such as water vapor and/or organic gases, in the arrangement. Water

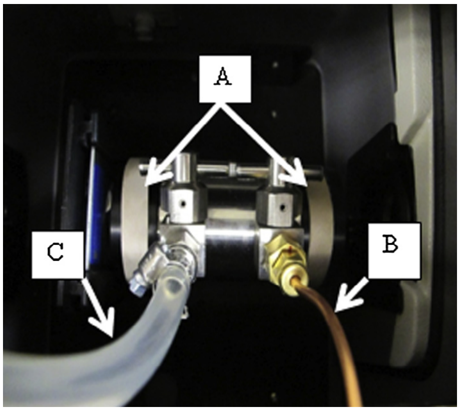

Fig. 3. The high pressure optical cell mounted in FTIR spectrometer to track emitted gases from the coal cores during shockwave experiments. A: KBr windows, B: High-pressure line, and C: Exhaust line.

vapor bands do not interfere with the measurements of the CO_2 vibrational modes. If a CO_2 pressurized coal core degasses with or without the impact of sudden shockwaves, then CO_2 vibrational bands in our FTIR system would be observed. Carbon dioxide produces strong stretching oscillators at $\sim$2345 cm^{-1} and bending vibrational modes at $\sim$667 cm^{-1}. It is difficult to control the amount of CO_2 emitted from the coal cores, especially CO_2 pressurized cores, when subjected to shockwaves. The amount of emitted CO_2 gas in the optical cell may saturate the MTC detectors even though the emitted gas is continuously being diluted by the injection of N_2. The intensity of the observed vibrational modes may not scale with the amount of gas in the cell, especially when the Beer–Lambert law is not being strictly obeyed. Therefore, the observed vibrational modes' intensity behavior should be visualized as a trend rather than the absolute amount of CO_2 emitted.

2.3. CO_2 pressurized coal cores

The coal cores were transferred to aluminum containers, and the containers were placed in a high pressure vessel (Parr Instruments Co.), which could be pressurized (ambient $\leqslant P \leqslant 27$ MPa) with CO_2. A SFT-10 supercritical fluid CO_2 pump (Supercritical Fluid Technologies, Inc.) was used to pressurize the vessel. Typically, Illinois unmineable coal seams are not very deep ($\sim$340 m), therefore, the CO_2 injection pressure was limited to 6.9 MPa. The high pressure vessel was maintained at the desired CO_2 pressure for 72 h. After 72 h of adsorption and/or absorption of CO_2, the high pressure pump was shut off, and the pressure vessel was slowly bled so that the samples could be removed from the vessel. In general, it took one hour to bleed the gas from the vessel before the coal cores could be extracted. Special attention was paid to whether it was feasible to collect any fluids which may have come out from the coal samples when they were pressurized with CO_2 in the high pressure vessel. However, no fluids were observed being extracted from the coal samples when they were pressurized with CO_2. In sample preparation, the coals had been dried at low pressure at 50 °C. As such, it was felt that maybe all the fluids had been removed during the vacuum drying. Cottage Grove coal chunks, which were not machined or vacuum dried, were subjected to high pressure CO_2 at 10.35 MPa. Again, no fluids were observed when the samples were extracted during the pressurization experiments. After recovering CO_2 pressurized coal cores from the high pressure vessel, the cores were immediately transferred to the high pressure die system for shockwave experiments. Table 1 summarizes the experimental parameters used to ascertain the fate of adsorbed/absorbed CO_2 in bituminous coal cores, which were pressurized with CO_2.

3. Results and discussion

The main focus of this research is on how shockwaves may affect the fate of sequestered CO_2 in coal seams. The assumption is that during seismic activity, whether manmade or natural, leakage pathways through the caprock are established. Arguments have been presented that the large-scale injection of CO_2 may induce seismicity, resulting in a compromise of the caprock seal integrity [7,9]. However, some researchers believe that the seal integrity will be maintained during induced seismicity [9]. At present, no conclusive evidence is available to support one view point or the other. Moreover, these arguments do not take into account any potential natural seismic activity, which may originate from unknown faults. The natural seismic activity could be much more severe than the CO_2 induced activity. It is known that CO_2 interacts with coal both chemically and physically [2,14,15], thus, it may be resistant to emission from coal under external perturbations. Therefore, these results may provide information about whether during seismic activity CO_2 would stay sequestered in coal seams.

3.1. Effects of shockwaves on non-pressurized samples

In the first set of experiments, an attempt was made to establish a baseline behavior for coal (CGC-CS) cores and pumice stone (PPS) in which the non-pressurized cores were subjected to shockwaves. Figs. 4 and 5 show the FTIR spectra of emitted CO_2 from Cottage Grove coal and pumice stone cores when they were subjected to shockwave experiments, respectively. For the CGC-CS core, the samples were allowed to degas for 10 min in the shockwave setup prior to subjecting them to shockwaves. It should be noticed that no CO_2 bands were observed prior to 10 min, indicating no gas emission. However, once the shockwaves were applied to the CGC-CS core, very weak vibrational bands were observed in the frequency range of 2400–2100 cm^{-1}, indicating that some CO_2 was emitted from the coal. Because this coal core was not pressurized

Table 1
Parameters used for shockwave experiments on CO_2 pressurized Cottage Grove Illinois bituminous coal cores. The cores were subjected to a compressive shock of 0.374 MPa under atmospheric pressure in a high pressure die.

Sample ID	Pressurized with CO_2	CO_2 Pressure (MPa)	Time under CO_2 Pressure (h)	Shockwave application after degassing at atmospheric pressure in high pressure die (min)
Cottage Grove coal control sample (CGC-CS)	No	–	–	10
Porous pumice stone (PPS)	No	–	–	10
Cottage Grove coal sample 1 (GCC-S1)	Yes	6.9	72	51
Cottage Grove coal sample 2 (GCC-S2)	Yes	6.9	72	4 (first shock) 25 (second shock)

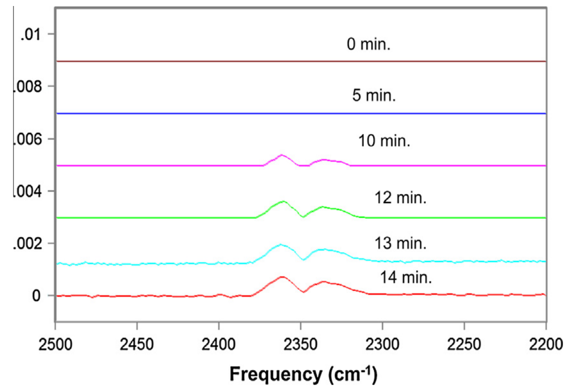

Fig. 4. Effects of the shockwaves on the emission of CO_2 from an un-pressurized Cottage Grove coal core (CGC-CS). Shockwaves were applied at 10 min. The spectra have been displaced along the *y*-axis (absorbance) for easy comparison.

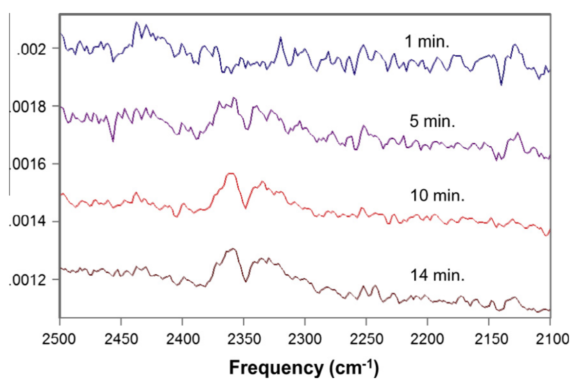

Fig. 5. Effects on the emission of CO_2 from an un-pressurized porous pumice stone (PPS) core. The shockwaves were applied at 10 min. The spectra have been displaced along the *y*-axis (absorbance) for easy comparison.

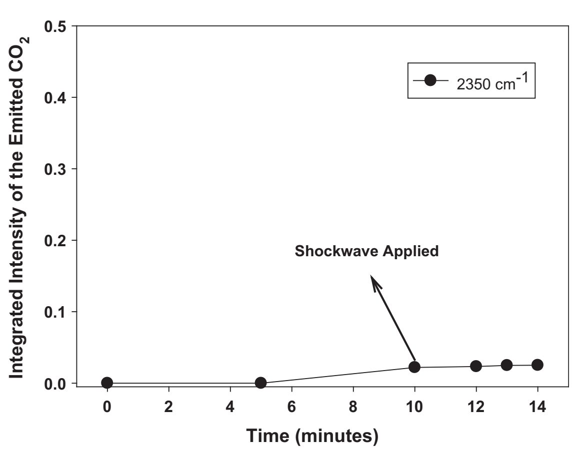

Fig. 6. Effects of shockwaves on the integrated intensity (arbitrary units) of the stretching mode of the emitted CO_2 from an un-pressurized Cottage Grove coal (CGC-CS) core.

with CO_2, the potential sources of the observed CO_2 vibrational bands most likely are due to gas adsorbed in the coal cores either in the seam or when the samples were being machined for experiments. The intensity of the emitted CO_2 bands as a function of time is graphed in Fig. 6.

It can be seen from Figs. 5 and 7 that when a highly porous medium like PPS core is subjected to shockwaves no discernible

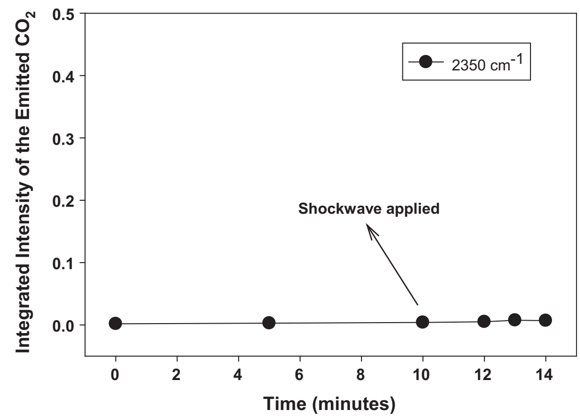

Fig. 7. Changes in integrated intensity (in arbitrary units) of the vibrational bands of CO_2 as a function of exposure time for an un-pressurized pumice stone (PPS) core. The shockwaves to the core were applied at 10 min.

vibrational bands of CO_2 gas were observed, suggesting no CO_2 emission. The fact that no CO_2 gas was emitted from the PPS core further supports the argument that the CO_2 bands observed from non-pressurized Cottage Grove are due to most likely inherent CO_2 in the coal.

3.2. Effects of shockwaves on CO_2 pressurized samples

To understand how CO_2 pressurized coal would behave if the caprock was compromised either via fracture or seepage pathways developing, a 6.9 MPa pressurized coal core (hereafter labeled CGC-S1) was allowed to degas at atmospheric pressure in the closed cell system for approximately 50 min. This degassing was in addition to ~1 h of degassing required for extracting the coal core from the high pressure (6.9 MPa) CO_2 vessel and transferring it to the closed cell system. Fig. 8, which shows the intensity of the vibrational bands of emitted CO_2, indicates how much and how fast CO_2 was emitted from the Illinois bituminous coal as a function of time. In the system, nitrogen was used as a purge gas to continuously drive gases out of the FTIR optical gas cell (see Figs. 1 and 2) to the exhaust system. Therefore, the high pressure cell system monitors the gases being emitted from the coal cores as a function of time. As the exposure time to atmospheric pressure increased, the intensity of the vibrational bands steadily decreased, which can be clearly seen in Fig. 8. The results suggest that when CO_2 pressurized coal cores were exposed to atmospheric conditions, massive amounts of CO_2 were emitted from the Illinois bituminous coal during the first 50 min. Fig. 9 shows a comparative

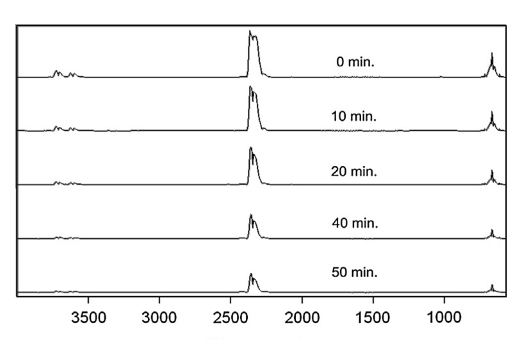

Fig. 8. The FTIR spectrum of the gases emitted from the pressurized coal (CGC-S1) core under atmospheric pressure conditions. The spectra have been displaced along the *y*-axis (absorbance) for easy comparison.

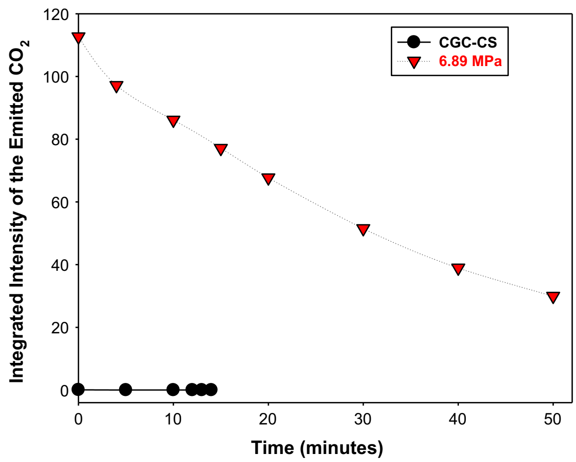

Fig. 9. Changes in the integrated intensity (in arbitrary units) of the vibrational bands of CO_2 as a function of exposure time for (a) the control (CGC-CS) core (non-pressurized) and (b) the pressurized (CGC-S1) core.

behavior of the intensity as a function of time of the observed vibrational CO_2 bands for pressurized and non-pressurized Cottage Grove coal cores. From the figure, it can be seen that while the intensity of the non-pressurized core remained unchanged, the intensity of the emitted CO_2 for the pressurized core exponentially decreased as a function of time. Thus, it is reasonable to conclude that if leakage pathways develop through the caprock, the emission of the sequestered CO_2 from Illinois bituminous coal would be very rapid, i.e., on a timescale of less than an hour. Moreover, it appears that the major fraction of the sequestered gas would be emitted during the first few minutes. As the difference in the pressure is expected to be significant between the unmineable coal seam and the surface, it would not be surprising if rapid and significant amounts of sequestered CO_2 are ejected. The results presented in Figs. 8 and 9, however, do not answer whether coal, which is known to react with CO_2 physically and chemically, still continues to hold significant amounts of CO_2 even if leakage pathways have been established.

After allowing the CO_2 pressurized CGC-S1 core to emit gas under atmospheric conditions for 50 min, the core was subjected to a 0.374 MPa (54 psi) shockwave at the 51 min mark. As can be seen from Fig. 10, on the application of the shockwave, additional CO_2 was ejected from the coal core. The intensity of the emitted CO_2 jumped in the gas cell on the application of the shockwave at the 51 min, and the intensity of the emitted gas further increased at the 52 min. Thereafter, the intensity of the CO_2 rapidly decreased as the purging gas swept out the gases which were emitted on the application of the shockwave. Results presented in Fig. 11 suggest that almost all of the CO_2, which was either adsorbed or absorbed in the sample, was emitted when the shockwaves were applied to the coal core.

In a second experiment, the Cottage Grove coal core (hereafter listed as CGC-S2), which was pressurized with CO_2 at 6.9 MPa, was allowed to emit CO_2 for 5 min in the closed cell system at atmospheric pressure before a 0.374 MPa shockwave was applied to the sample. Again, the 5 min degassing was in addition to the degassing which occurred in removing the core from the high pressure vessel and transferring it to the closed cell system as described for CGC-S1. For this experiment, the emphasis was placed on evaluating the fate of sequestered CO_2 if the aftershocks were more closely spaced in time. Again, the assumption was that during primary seismic activity the caprock had been compromised. As the pressurized sample was exposed to the atmospheric pressure in the closed system, massive amounts of emitted CO_2 were observed from the core (see Figs. 11–13). However, this is

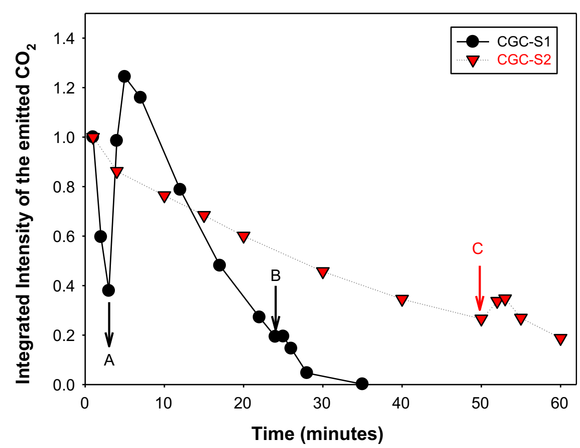

Fig. 11. Changes in the integrated intensity (in arbitrary units) of the vibrational bands of the emitted CO_2 as a function of exposure time for cores pressurized to 6.9 MPa of CO_2. Pressurized coal (CGC-S1) core was allowed to emit CO_2 for 50 min at atmospheric pressure prior to the application of shockwave at the minute 51 (point C). Pressurized coal (CGC-S2) was allowed to emit CO_2 at atmospheric pressure for 4 min before first shockwave was applied (point A). A second shockwave (point B) was applied after 20 min of the first shockwave.

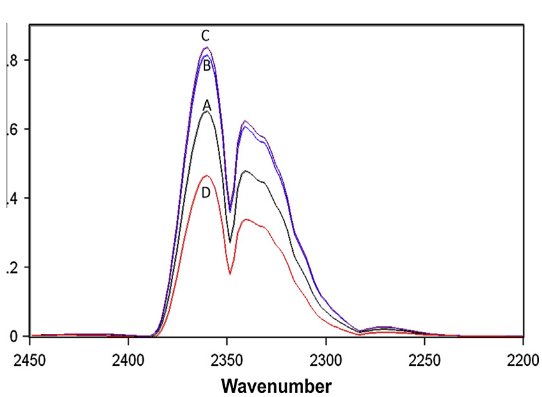

Fig. 10. Effects of the shockwave on the emission of CO_2 from pressurized coal (CGC-S1) core. A: Spectrum after 50 min of degassing at atmospheric pressure, prior to the applied shockwave. B: Spectrum at 51 min when the shockwave was applied. C: Spectrum from 1 min after shockwave application. D: Spectrum from 8 min after shockwave application. The *y*-scale represents absorbance.

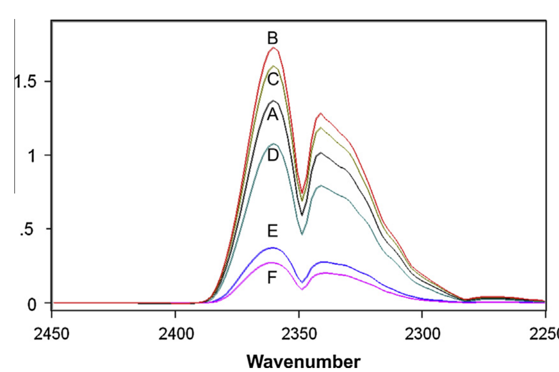

Fig. 12. Effects of the shockwave on the emission of CO_2 from coal (CGC-S2) core. A: Spectrum after 1 min of degassing at atmospheric pressure. B: Spectrum at minute 5 when the shockwave was applied. C: Spectrum from 2 min after shockwave application. D: Spectrum from 7 min after shockwave application. E: Spectrum from 17 min after shockwave application. F: Spectrum from 19 min after shockwave application. The *y*-scale represents absorbance.

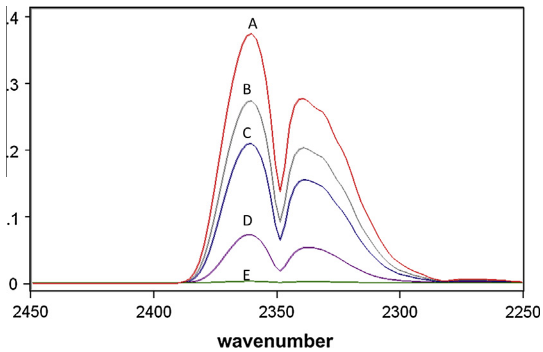

Fig. 13. Effects of the shockwave on the emission of CO_2 from coal (CGC-S2) core. A: Spectrum from 17 min after shockwave application. B: Spectrum from 20 min after a first shockwave was applied. C: Spectrum from 1 min after the second shockwave application. D: Spectrum from 3 min after the second shockwave application. E: Spectrum after 10 min of the second shockwave application. The *y*-scale represents absorbance.

to be expected because of the pressure differences involved, i.e., pressure difference between the die and the optical cell. It is worth pointing out that because the cylindrical core is confined in a tightly-fitted hardened stainless steel die, the compressive waves generated on the application of the shock would be complex as the core would experience a primary compressive wave followed by reflections at the boundaries. However, these reflective waves are also expected in nature as the primary wave encounters different medium interfaces.

On the application of the shockwave at the 5 min mark, observations showed a massive ejection of CO_2 from the core as can be seen from Figs. 11 and 12. The intensity of the emitted gas decreased rapidly and exponentially during the next 20 min. At that stage, a second shockwave of 0.374 MPa was applied. Only a very minor increase in the intensity of the emitted gas was observed as can be seen in Figs. 11 and 13. During the next 10 min, almost all the sequestered gas in the coal core was emitted. Fig. 14 shows a photograph of the core (CGC-S2) after the core had been subjected to shockwave experiments. Clearly, the core showed brittle failures during the shockwave experiments. A number of fractures were also initiated in the coal core. These fractures, along with the brittle failure, may have facilitated the emission of the CO_2 from the coal core during shockwave experiments. However, there was no evidence that CO_2 molecules remained trapped in the coal pores after the application of the shockwaves.

Fig. 14. The photograph of the Cottage Grove bituminous coal (CGC-S2) core after it underwent shockwave experiments.

4. Summary and conclusions

At present, there is a lack of consensus on whether seismic activity could compromise the caprock in the areas where potential geological CO_2 sequestration could occur. Nevertheless, the public acceptance of the large-scale geological CO_2 sequestration would require evidence that it is safe. One potential source for CO_2 sequestration is unmineable coal seams. Therefore, experiments were undertaken to identify the fate of CO_2 pressurized Cottage Grove Illinois bituminous coal cores under conditions which may be prevalent during seismic activity, whether manmade or natural. A closed experimental system was developed in which pressurized coal cores could be subjected to compressive shockwaves, while the emission of CO_2 from the coal cores could be simultaneously monitored. The following is concluded from the experiments: (i) Non-CO_2 pressurized coal and porous pumice stone cores showed no significant emission of CO_2 when they were subjected to 0.374 MPa shockwaves. (ii) A massive loss of CO_2 occurred rapidly and exponentially from the coal cores, which were pressurized with 6.9 MPa of CO_2, when they were exposed to atmospheric pressure in the system. Thereafter, the rate of emission of CO_2 decreased though CO_2 continued to be ejected from the coal. However, this is to be expected as the pressure difference between the coal cores and atmosphere decreased. (iii) The Illinois bituminous coal did adsorb and/or absorb CO_2, and this CO_2 was not emitted by simply exposing the CO_2 pressurized coal to atmospheric pressure conditions in the closed system. However, all the adsorbed/absorbed CO_2 was ejected when the Illinois bituminous coal cores were subjected to compressive shocks as moderate as 0.374 MPa. (iv) The results suggest that almost all the CO_2 would be emitted in less than 60 min if the caprock had been compromised during the primary seismic activity and the coal cores experienced shockwaves during any subsequent shocks. Therefore, the conclusion that massive, if not total, emission of the sequestered CO_2 in Illinois bituminous coal during seismic activity cannot be discounted.

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References

[1] National Energy Technology Laboratory (USA). Carbon sequestration technology Roadmap and Program Plan 2007. <http://www.netl.doe.gov/technologies/carbon_seq/refshelf/project%20portfolio/2007/2007roadmap.pdf> (accessed 10.31.2010).
[2] White CM, Smith DH, Jones KL, Goodman AL, Jikich SA, LaCount RB, et al. Sequestration of carbon dioxide in coal with enhanced coalbed methane recovery – a review. Energy Fuels 2005;19:659–724 [and references therein].
[3] National Energy Technology Laboratory (USA). Monitoring, verification, and accounting of CO_2 stored in deep geological formations. Report DOE/NETL-311/081508, <www.netl.doe.gov>; 2009.
[4] Haszeldine RS. Carbon capture and storage: how green can black be? Science 2009;325:1647–52.
[5] Orr Jr FM. Onshore geologic storage of CO_2. Science 2009;325:1656–8.

[6] Person M, Banerjee A, Rupp J, Medina C, Lichtner P, Gable C, et al. Assessment of basin-scale hydrologic impacts of CO_2 sequestration, Illinois basin. Int J Greenhouse Gas Control 2010;4:840–54.

[7] Zoback MD, Gorelick SM. Earthquake triggering and large-scale geological storage of carbon dioxide. PNAS 2012;109:10164–8. Reply to Juanes et al.: Evidence that earthquake triggering could render long-term carbon storage unsuccessful in many regions. PNAS 2012;109:E3624.

[8] Mazzoldi A, Rinaldi AP, Borgia A, Rutqvist J. Induced seismicity within geological carbon sequestration projects: maximum earthquake magnitude and leakage potential from undetected faults. Int J Greenhouse Gas Control 2012;10:434–42.

[9] Kramer D. Scientists poke holes in carbon dioxide sequestration. Phys Today 2012;65(8). 22.

[10] West M, Sanchez JJ, McNutt SR. Periodically triggered seismicity at Mount Wrangell, Alaska, after the Sumatra earthquake. Science 2005;308:1144–6.

[11] West RD, Markevicius G, Malhotra VM, Hofer S. Variations in the mechanical behavior of Illinois bituminous coals. Fuel 2012;98:213–7.

[12] Markevicius G, West RD, Malhotra VM, Hofer S. Does Illinois bituminous coal manifest glass transition: DMA, DSC, and FTIR results. Fuel 2012;103:220–6 [and references therein].

[13] Tillman D, Duong DND, Harding NS. Solid fuel blending principles, practices, and problems (Walthan USA). Butterworth-Heinemann; 2012.

[14] Romanov R. Coal chemistry for mechanical engineering: from macromolecular thermodynamics to reservoir simulation. Energy Fuels 2007;21:1646–54.

[15] Romanov VN, Ackman TE, Soong Y, Kleinman RL. CO_2 storage in shallow underground and surface coal mines: challenges and opportunities.