Measuring the gas content of coal: A review

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Abstract

Coalbed gas content measurements are commonly used in mine safety as well as coalbed methane resource assessment and recovery applications. Gas content determination techniques generally fall into two categories: (1) direct methods which actually measure the volume of gas released from a coal sample sealed into a desorption canister and (2) indirect methods based on empirical correlations, or laboratory derived sorption isotherm gas storage capacity data. Direct gas content determination techniques may be further subdivided into quick-crushing and extended desorption methods. The quick-crushing methods are primarily used in mine safety applications outside the United States, but have also been used for resource recovery applications. Quick-crushing methods rely on crushing the coal sample soon after collection to release all the desorbable gas, thus significantly shortening the amount of time required for desorption measurements. However, some data useful for resource recovery applications are lost. Extended desorption techniques are most commonly used for resource assessment and recovery applications where information on desorption rates is useful for reservoir modeling, and for fundamental coalbed methane research. Extended desorption methods allow the gases in the coal sample to desorb under controlled laboratory conditions until a defined low desorption rate cutoff point is reached. The sample may then be crushed to measure the amount of gas remaining within the sample. Direct method techniques for gas content measurement are the focus of this paper.

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volumes cannot be directly measured and therefore must be estimated from the subsequently measured gas volume data. Since the lost gas is an estimated quantity, it is generally considered to be the least reliable component of the total gas content. Considerable research effort has been expended to evolve a more versatile and accurate lost gas estimation procedure from that developed by the former USBM [1] (US Bureau of Mines) (Kissell et al., 1973) from the work of Bertard et al. (1970).

The volume of gas lost prior to sealing a coal sample into a desorption canister generally depends on sample retrieval time, physical character of the sample, the type of drilling fluid, and water saturation/relative amount of free gas. Virtually all methods for estimating lost gas benefit from minimizing the lost-gas time over which measured desorption data must be extrapolated. Wireline core retrieval from coalbed depths of less than 610 m (2,000 ft), common in most mining areas in the United States, is relatively quick and generally requires only a few minutes to reach the surface. The retrieval time plus the time required to remove the sample from the core barrel, determine the depth interval of the coalbed and individual samples, inspect and describe the coal sample(s) to be tested, and finally sealing the sample(s) in the canister(s) can generally be accomplished in under one hour, and in many instances in less than 30 minutes. Under these conditions, the lost-gas time is relatively short, thus reducing the lost-gas volume and therefore, the potential error inherent in the estimation techniques.

Lost gas estimation becomes a more significant issue under several circumstances most commonly associated with commercial production operations. Lost-gas times are generally longer (> 1 h) in many of the commercial coalbed methane applications where depths may be greater than those associated with mining, and/or conventional coring methods are utilized. Extended lost-gas times can increase any associated error by increasing the fraction of lost gas relative to the total gas content.

Kissell et al. (1973) and McCulloch et al. (1975) demonstrated that the physical character of the retrieved coal sample can influence the desorption rate and hence the volume of lost gas that must be estimated. Blocky coals which remain intact during coring and subsequent retrieval emit their adsorbed gas at a relatively slow rate. However, friable coals which tend to break apart into smaller fragments, release their adsorbed gas faster because of the shorter diffusion distances. The density of the drilling fluid influences the time during sample retrieval when desorption is assumed to begin, i.e., when the hydrostatic pressure of the drilling fluid equals the reservoir pressure of the coalbed.

The final factor influencing the accuracy of the lost gas estimation is the water saturation and associated level of free gas in the virgin coalbed from which the sample is obtained. Most estimation methods are based on the assumption that the lost gas is desorbed gas (behaving according Fick's law of diffusion) and all the measured gas volumes used in extrapolation are also desorbed gas. Many coalbeds are essentially water-saturated and contain only a relatively small volume of free gas. However, there

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[1] The US Congress in 1996 directed that the US Bureau of Mines be abolished. USBM health and safety research was subsequently transferred to the National Institute for Occupational Safety and Health.

1. Introduction

The accumulation of methane in underground coal mines continues to be a safety problem in the United States and around the world. Measuring the quantity of methane contained within a coalbed can be an important step in evaluating the potential severity of gas problems in new mines or in unmined areas of existing mines. Gas content testing can be included in the exploratory core drilling program usually conducted during the planning phase of mine development (Diamond, 1979). An early assessment of the potential for methane emission problems provides the greatest amount of lead time to incorporate longer term gas drainage techniques into the mine development plan (Diamond, 1994). Once mining is underway, gas content testing can be used periodically to assess gas content conditions ahead of mining.

Whereas mine safety was initially the primary purpose for measuring the gas content of coalbeds, the potential for commercial coalbed methane production has resulted in an increased interest in this technology. Coalbed gas content data are used for the calculation of gas resources and as input data for reservoir models and production simulators to forecast gas production and to evaluate methane control options for underground coal mining.

2. Gas content component parts

Gas is stored in coalbeds in a manner different from conventional reservoirs. Yee et al. (1993) described the gas in coal as existing primarily in a ''condensed, near liquid-like state because of physical sorption'', unlike the free gas existing in the pores of conventional reservoir rock. Due to the different gas storage mechanism associated with coal, formation evaluation methods common in the conventional oil and gas industry can not be applied to coalbed reservoirs to determine the volume of gas in place. Thus gas content determination methods have been developed to measure the volume of gas sorbed within the micropores of coalbed gas reservoirs.

The most commonly used gas content determination methods subdivide the total gas content of a coal sample into three parts: lost, desorbed and residual gas. Each of these parts is generally measured or estimated by a different procedure, and then combined to yield the total gas content of the sample. Even though the various gas content determination methods generally use similar terminology for the individual components of the total gas content, the individual components of the various methods may not be directly comparable due to variations of procedural conditions between some methods. Mavor and Pratt (1996), McLennan et al. (1995) and Mavor et al. (1994) present comprehensive analyses of the possible errors associated with measurement of these gas content component parts by commonly used testing methodologies.

2.1. Lost gas

The lost gas is that portion of the total gas that escapes from the sample during its collection and retrieval prior to being sealed into an airtight desorption canister. Lost gas are coalbed gas reservoirs that are not water-saturated, which contain larger volumes of free gas. Some portion of this free gas will escape during sample retrieval and will not be accounted for by lost gas estimation methodologies based on diffusion of desorbed gas.

2.2. Desorbed gas

Once a coal sample is sealed in the desorption canister, the desorbing gas accumulates and can be measured directly, commonly by some variation of the water displacement method first described by Bertard et al. (1970) and later refined by Kissell et al. (1973). A more accurate method developed by the USBM to measure the low volumes of gas desorbed from samples of oil shale (Schatzel et al., 1987), is based on measuring pressure differentials in the canister as gas is released, then utilizing the ideal gas law to determine the desorbed gas volume.

2.3. Residual gas

The volume of gas desorbing from a coal sample gradually declines with time. Desorption measurements for the extended desorption techniques are terminated at some point when an arbitrary low desorption rate is reached. This rate may be reached in a matter of days for very friable samples or can take months for some blocky coals. Generally, when the desorption rate reaches an established termination point, some volume of gas remains in the sample. Traditionally, this residual gas has been thought of as gas that is 'trapped' within the coal structure due to slow diffusion rates. Bertard et al. (1970) and Levine (1992) suggest that the residual gas may not be diffusion dependent, but in part, represents gas remaining in equilibrium under approximately 1 atm of methane pressure in the desorption canister.

The residual gas volume can be determined by crushing the sample in an airtight container and measuring the volume of gas released by the same method as that used for the desorbed gas (Diamond et al., 1986). The volume of residual gas measured in the laboratory for samples subjected to elevated temperatures to approximate actual reservoir conditions will probably be less than would have been measured if the sample had equilibrated to ambient laboratory temperature during desorption monitoring.

Analysis of the gas content component parts for 1,500 coal samples from 250 coalbeds in the United States (Diamond et al., 1986), shows that residual gas can comprise 40 to 50% of the total gas content, in particular for relatively low-rank (high volatile-A bituminous) blocky coalbeds. In contrast, friable, high rank (medium to low volatile) bituminous coalbeds typically had less than 10% residual gas. Caution must be used in evaluating the resource recovery potential of coalbeds with a high residual gas content, since it may represent methane that will not readily flow to a methane drainage borehole under field conditions. Residual gas may also represent a portion of the total gas content that will not be admitted into a mine atmosphere either from migration to the mine openings from the surrounding coal or from the mining of the coal at the face.

3. Direct versus indirect gas content determination methods

3.1. Direct methods

The gas content of a coal sample can be determined by several available direct measurement techniques. These techniques can generally be divided into quick-crushing and extended desorption determination methods. The quick-crushing techniques are most commonly used outside the United States for assessment of gas conditions ahead of the active production face. The coal samples are usually obtained from underground drill holes. Instead of waiting for months to obtain results, total gas yield is available within a matter of days. Thus quick-crushing methods are appropriate for the mining applications for which they were intended. However, by crushing the sample early in the desorption process, it is impossible to determine the relative amounts of desorbed and residual gases, and the sorption time (time to release 63% of total sorbed gas) commonly used in coalbed gas reservoir models (Sawyer et al., 1987).

The extended desorption gas content measurement techniques allow for a sample to desorb gas until a low desorption rate cutoff point is reached. The sample may then be crushed to a powder to quickly release any gas remaining within the coal. These techniques are most common in the United States and are used for both mining, coalbed methane resource recovery applications, and basic research. The coal samples to be tested are generally fresh core or drill cuttings obtained from boreholes drilled from the surface.

Pressure coring is an alternative direct measurement method used to obtain a coal sample at reservoir pressure, thus eliminating the need for determining lost gas (Owen and Sharer, 1992). Pressure cores are generally considered the standard against which other gas content determination methods are evaluated. However, pressure cores are not without their own problems, including high cost.

3.2. Indirect methods

Gas contents can be estimated indirectly based on sorption isotherm data (Kim, 1977) or empirical estimation curves of measured gas content results plotted against other measurable variables such as coalbed depth and coal rank (Diamond et al., 1976; McFall et al., 1986). Laboratory derived sorption isotherms describe the quantitative relationship between adsorbed methane at varying pressures and a constant temperature, and provide a measure of the maximum methane sorption or storage capacity of the coal sample. Thus, gas content estimates based on sorption isotherm data do not necessarily result in accurate in situ gas content values. Since all coalbeds are not fully saturated with methane, especially those at shallow depths, the isotherm-based methods may over estimate the actual gas content.

Efforts to estimate the gas content of coalbeds utilizing wireline geophysical logging tools have also been attempted (Mullen, 1989). The wireline logging method does not directly measure the gas content of the coalbeds exposed in the wellbore. It is essentially an empirical estimation curve technique. Algorithms relating gas content to apparent coal rank are derived from actual gas content and coal proximate analysis data from cores obtained in the geographical area of interest. Log-derived coal property data are then used to estimate gas content as a function of coal rank and depth.

Indirect methods can serve as a preliminary assessment tool for mine planning purposes or targeting potential areas for commercial coalbed methane exploration. Whenever possible, however, engineering and/or economic decisions should include data from actual direct measurement tests.

4. Sampling strategies

Coal samples for gas content testing are commonly obtained from wireline or conventional cores and drill cuttings from production wells or test boreholes. Core samples or drill cuttings may also be obtained from boreholes drilled underground. In general, coal cores are preferable to cuttings. Due to their larger size and lower ratio of surface area to volume, cores typically have slower initial desorption rates, effectively reducing the amount of gas lost during sample retrieval. Gas content values obtained from drill cuttings should generally be considered minimum values because of the difficultly in applying lost gas estimation techniques to this type of sample.

An issue that frequently arises at the drill site is how to select samples for gas content testing. It is not uncommon for gas contents to vary over the length of a coal core due to coal compositional changes, primarily varying mineral matter content. If samples are obtained from cores, it is preferable to test the entire recovered coal section. However, it is generally good practice to divide the coal core into several samples instead of placing the entire coal section into a single desorption canister.

When multiple samples are tested from the same coal core, it is recommended that the samples be selected relative to naturally occurring breaks in the coalbed, such as shale partings, which can be left out of the test sample. However, this should be noted so that the untested material can be accounted for in resource calculations.

5. Selected gas content determination methods

The gas content testing methods summarized in this paper were selected for their historical value, innovation or uniqueness, and common usage. Most of the methods are based on the work of Bertard et al. (1970) and the USBM (Kissell et al., 1973), with the primary differences being the equipment used to measure desorbed gas volumes, and the technique for estimating the volume of lost gas. Both the nomenclature and units of measure used by the originators of the various described methods have been utilized, hence the occasional variability of terminology for similar concepts.

5.1. Bertard's direct method

The original direct method was developed in France by Bertard et al. (1970). Similar methods are still in general use for gas content testing in high gas emission underground coal mines in many European mining operations (C. Tauziede, pers. commun., 1996).

Bertard's methodology was primarily designed for the testing of drill cuttings collected from horizontal holes drilled in underground coal mines. The total gas content of a coal sample was separated into three component parts, but the sample had to be transferred to a different container for the measurement of each component by a different apparatus.

The methodology described by Bertard et al. (1970) was based on experimental and theoretical studies on the sorption and diffusion of methane in coal. These studies included the finding that early in the desorption process the volume of gas released was proportional to the square root of time. This finding is the basis for determining the quantity of gas lost by the sample from the moment when it was extracted from the coalbed to when it was transferred into a transport container. A 10 g coal sample is collected from the borehole underground and immediately sealed in a glass flask connected by tubing to a U-tube manometer (collectively referred to as a desorption meter). Plaizier and Hucka (1991) investigated the application of similar methodology using a bubble desorbometer for use in mining operations in the western United States.

Bertard et al. (1970) estimated the lost gas volume using desorption meter data and a derived formula that they considered valid, as long as the lost gas volume represented less than 20% of the total gas content, necessitating the speedy recovery and sealing of the drill cuttings into the desorption meter. At the end of the lost gas determination procedure, the sample is transferred to a second container for transport out of the mine to the laboratory, where the gas volume desorbed during transport is measured.

Finally, the sample was sealed into a third container for crushing and determination of the volume of gas remaining in the coal. This gas volume was measured in a graduated cylinder suspended over a pan of water into which the gas released by crushing was collected. The total gas content of the sample was then the total of the three component parts, expressed in cm^3/g.

Bertard et al. (1970) noted that the final results could be presented either in terms of the temperature and pressure conditions of the underground sampling site for the site-specific mining application, or at STP conditions for a ''stricter comparison of the desorbable concentrations of different seams.'' It was also noted that the ''desorbable concentration is always referred to pure coal'' necessitating a correction for contained mineral matter content. Bertard et al. (1970) also recognized the potential for using this methodology with core samples, but emphasized the importance of short sample recovery time to ensure accurate lost gas estimates.

5.2. US Bureau of Mines direct method

The coalbed gas content testing procedure commonly referred to as the USBM direct method (Kissell et al., 1973) was an adaptation and simplification of the method developed by Bertard et al. (1970). The initial purpose of the USBM method was to determine the gas content of virgin coal core samples for use in estimating ventilation requirements for new mines. Laboratory experiments confirmed that lost gas assumptions for coal cuttings proposed by Bertard et al. (1970) could also be applied to the larger sized coal core samples that would have a longer sample recovery (lost gas) time.

The USBM direct method eliminated the multiple sample containers and associated measurement techniques used by Bertard et al. (1970) to determine the component parts

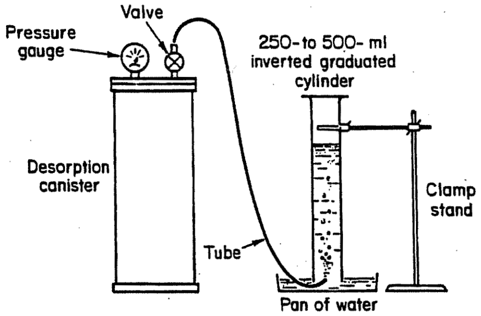

Fig. 1. USBM direct method gas volume measurement apparatus.

of the total gas content. Standard desorption canisters were constructed from ≈ 0.3 m (1.0 ft) long sections of ≈ 10.2 cm (4.0 in.) diameter aluminum pipe (Fig. 1). All gas volume measurements were made by periodically releasing the accumulated gas into a water filled inverted graduated cylinder (Fig. 1).

Kissell et al. (1973) proposed two alternate approaches to estimate time zero and cumulative lost gas time. If the hole was cored with water or drilling mud, desorption was assumed to begin when the sample was halfway to the surface. The cumulative lost gas time (t_{lg}) would then be

$$t_{\mathrm{lg}} = (t_4 - t_3) + (t_3 - t_2)/2,$$

where t_2 is the time core retrieval began, t_3 the time core reached the surface and t_4 the time core sealed in desorption canister. If the hole was cored by air or mist, pressure release and gas desorption were assumed to begin at the first penetration of the coalbed by the core barrel. In this case, t_{lg} would be

$$t_{\mathrm{lg}} = t_4 - t_1,$$

where t_1 is the time the coalbed was first penetrated.

A graphical technique was proposed to estimate the lost gas volume (Q_1) based on several early direct measurements of desorbed gas after the sample was sealed into the desorption canister. Measurements of the desorbed gas volume are made every 15 to 20 min for the first several hours. These data are then plotted on a graph of cumulative desorbed gas versus the square root of desorption time. The initial linear portion of the desorption curve is extrapolated through the point on the x-axis representing the lost-gas time ($\sqrt{15}$ min, Fig. 2) to estimate the lost-gas volume.

The desorbed portion (Q_{d}) of the total gas content is measured periodically by the water displacement technique described above. At some point, gas desorption slows to a rate at which essentially little gas is emitted. McCulloch et al. (1975) proposed that desorption measurements be discontinued when daily emissions were less than 0.05 cm^3/g for five consecutive days, which was subsequently revised by Diamond and Levine (1981) to an average of 10 cm^3 of gas desorption per day for one week. Both of these guidelines are arbitrary; but whatever cutoff rate is used, it should be applied uniformly to all samples.

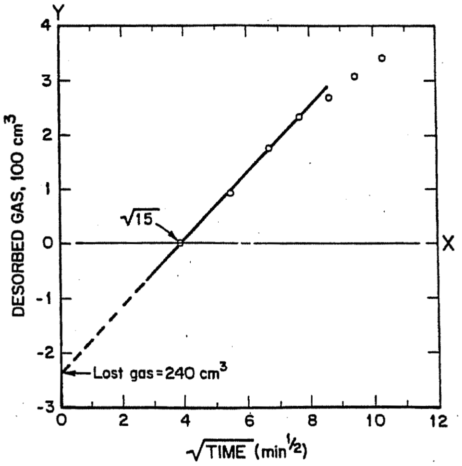

Fig. 2. USBM direct method lost gas estimation graph.

At the point when the periodic measurement of desorbed gas is discontinued, the residual gas (Q_r) is determined by crushing the sample to a powder (−200 mesh). The recommended procedure for determining the residual gas (Q_r) requires the transfer of all or a portion of the desorbed coal sample to a desorption ball mill canister for crushing on a roller mill (Diamond and Levine, 1981).

The volume of gas released is measured by the water displacement method after the sample cools to ambient temperature. The gas volume released by crushing is attributed only to the portion of the sample crushed to a powder. The total gas content of the sample is then

$$Q_t = (Q_l + Q_d)/M_t + Q_r/M_c, \tag{1}$$

where M_t is the total air-dried mass (weight) of the sample and M_c the air-dried mass (weight) of the sample crushed to a powder in the ball mill.

The value Q_t is calculated in cm^3/g, but is commonly converted to ft^3/st (= cm^3/g × 32) in the United States for ease in making gas resource calculations.

Due to the changing uses of the gas content data in the United States beginning in the early 1980's, several modifications to the USBM direct method were proposed. One of these modifications was designed to eliminate volumetric measurement errors due to the differential heads between the water level in the graduated cylinder and the pan (Fig. 1) by adjusting the water level in a separate reservoir vessel to that in the measurement vessel. Relative errors due to these differential pressures were estimated by TRW (1981) to range up to about 4%. Two examples of these alternative manometric apparatuses are shown in Fig. 3.

Another potential problem with direct method testing methods is related to the volume of head space (free space) left in the canister after the sample is inserted. Changes in ambient pressure and temperature on the head space volume between subsequent desorption readings can influence the resultant volumetric measurement. These changes can be either positive or negative depending on the net effects of both

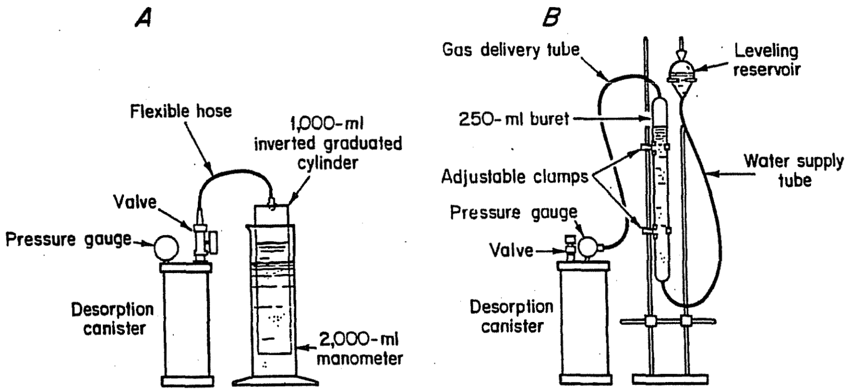

Fig. 3. Examples of manometric gas volume measurement apparatuses. Modified after: (A) Camp et al. (1992) and (B). TRW (1981).

temperature and pressure changes between readings. Since these changes in gas volume due to the head space effect tend to cancel themselves out over time, corrections for this problem were not included in the original USBM direct method test procedure. However, it was recommended that the volume of head space in the canisters be minimized by filling the canisters as full as possible to reduce possible errors associated with this problem. An even better solution is to customize the canisters to the diameter of the core and length of the sample to be collected. For those concerned with the loss of accuracy due to the head space effect, it is relatively easy to add a correction factor based on the ideal gas law. Circumstances of extreme variations in atmospheric pressure (e.g. elevation difference between collection location and laboratory) or temperature may necessitate head space effect corrections.

It is important to periodically collect samples of the gas desorbed to determine the actual constituents of the measured gas volume. In most cases, the gas is predominantly methane; however, other constituents are present. Kim (1973) reported that the largest constituent in coalbed gas after methane is usually CO_2 or N_2. In the United States, CO_2 has most commonly been found in the Pittsburgh Coalbed in the east (Kim, 1973) and several coalbeds in the western interior, including the Fruitland Coalbed in the San Juan basis (Rice, 1993). Rice (1993) also reports high concentrations of CO_2 for coalbeds in the Peoples Republic of China, Australia and Poland. Other constituents of coalbed gas may include minor amounts of higher hydrocarbons (primarily ethane), H_2, and He (Kim, 1973).

5.3. US Bureau of Mines modified direct method

Early mine development experience in the oil shale industry suggested that significant quantities of methane could be released during mining. Preliminary assessment of the low volumes of gas sorbed within the organic matter associated with oil shale indicated that the existing USBM direct method technique was not sufficiently precise or accurate for this application. A new gas content testing methodology was developed to more

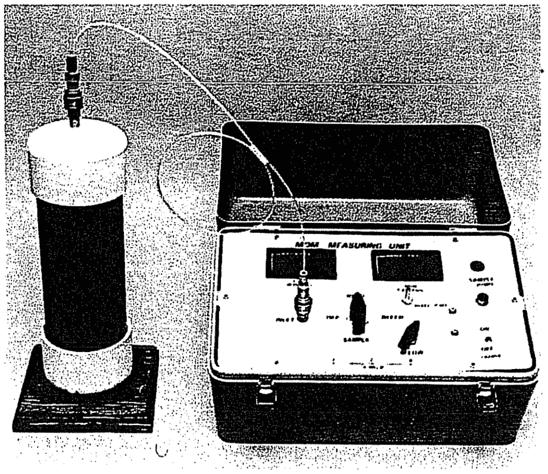

Fig. 4. USBM modified direct method instrumentation unit and field customized PVC desorption canister.

accurately measure the expected low gas volumes of oil shale samples. This new method also provided increased accuracy for determining the gas content of coal and other rocks where sorption is the primary gas storage mechanism.

The primary improvement of the modified direct method (MDM) was the abandonment of the water displacement apparatus for measuring desorbed gas volumes. Instead, the MDM test procedure relies on the measurement of differential pressures (pressure buildup between readings) and the ideal gas law to calculate the volume of gas released into the desorption canister at STP conditions (Schatzel et al., 1987). The MDM measurement apparatus utilizes pressure transducers with digital readouts that offer superior resolution compared with other instrumentation incorporated in conventional direct method gas content testing apparatuses.

The small size and ruggedness of the apparatus (Fig. 4) facilitates its use in the field, as well as in the laboratory. The inclusion of two pressure transducers permits a choice of overlapping pressure ranges for increased accuracy within each transducer's optimal range. A gas sampling port allows for collection of uncontaminated gas samples.

An additional innovation developed as part of the MDM is the use of canisters constructed of polyvinyl chloride (PVC) pipe. The internal diameter of the canister is sized as close as possible to the external diameter of the core samples. The canister is partially constructed and pressure tested in the laboratory with only one end cap. The other end cap (fitted with the quick-disconnect valve assembly, as illustrated in Fig. 4) is glued in place after the pipe is cut to size in the field to match the length of the actual coal sample. Customizing the desorption canisters to the actual size of the sample greatly reduces the head space volume in the canister.

The application of the MDM to coal samples, as described by Ulery and Hyman (1991), includes the determination of lost (Q_l), desorbed (Q_d) and residual (Q_r) gas components of a sample. As with the original USBM direct method, the lost gas (Q_l) is estimated by extrapolating early time periodic measured gas volumes to time zero, as shown in Fig. 2. The individual data points of desorbed gas volume (V_{dp}) at STP conditions are determined by the formula

$$V_{dp} = V_i - V_f,$$

where V_i is the gas volume in the desorption canister at the end of a desorption volume measurement time interval and V_f the volume of gas in the canister after releasing the accumulated desorbed gas volume.

V_i and V_f are calculated at STP conditions according to the ideal gas law

$$V_i \text{ (or } V_f) = (P_{amb} T_{std} V_{amb}) / (P_{std} T_{amb}),$$

where P_{amb} is the ambient pressure of gas in canister, P_{std} the standard pressure, T_{amb} the ambient temperature of gas in canister, T_{std} the standard temperature and V_{amb} the free space volume at T_{amb} and P_{amb}.

An advantage of the MDM gas volume measurement and calculation technique is that the head space effect correction is inherent in the calculation. Negative V_{dp} values, as well as positive values, are also easily measured with the MDM technique. This is not the case with the water displacement gas volume techniques where a negative pressure in the canister can draw water into the tubing connecting the measurement apparatus and the canister. A further advantage of eliminating the water displacement method of gas volume measurements is the elimination of gas dissolution problems associated with gases that have high solubilities, such as CO_2.

Desorption in the canisters is generally allowed to continue until the cutoff point previously defined for the USBM direct method test is reached. The desorbed gas volume (Q_d) is then the sum of the periodic gas measurements (V_{dp}). Prior to removing the coal sample from the canister, the head space is measured. However, to calculate apparent gas volumes as the desorption process is underway, an estimated head space volume is calculated by subtracting the estimated volume of the coal sample from the estimated internal volume of canister. A portion of the sample is crushed and the residual gas volume (Q_r) measured by the MDM. The final gas content of the sample (Q_t) is calculated according to Eq. (1). The final results are reported at a defined STP, gas species, and coal compositional (as-received versus ash- or mineral- matter-free) basis.

A common problem occurring in the desorption canisters are oxygen depletions, either through oxidation or perhaps adsorption (Popp et al., 1979; Ulery and Hyman, 1991). Gas samples are obtained for each MDM desorption measurement. Without these gas compositional analysis, the net change in volume between oxygen depletion and methane desorption would underestimate the true desorbed methane volume.

The oxygen depletion problem can be eliminated by purging the sample containers with an inert gas, but this entails added expense, as well as an additional complication to the testing procedure in the field. Even if the canisters are purged in the field with an inert gas, it is recommended that desorption readings be accompanied by a gas compositional analysis to determine volumetric changes in gas species desorbed over the duration of testing.

Ulery and Hyman (1991) compared MDM results with simulated direct method results derived from MDM data. They concluded that if the USBM direct method is conducted according to the recommended specifications and practices, reasonably accurate STP results can be obtained. However, the water displacement methods in general have been shown to be unresponsive to pressure differentials below about 5 to 8 cm H_2O. The most substantial loss of accuracy occurs when small, low gas content samples are placed into a large container resulting in a large free space volume. Errors of up to 100% were reported when the ratio between the desorbed gas volume and the free space in the canister is less than 2:1.

5.4. *Smith and Williams method*

Smith and Williams (1981) developed a variation of the direct method technique to address the problem of accurately determining the gas content of coal cuttings obtained from surface rotary-drilled boreholes. The lost gas portion of the total gas content was the focus of this water displacement measurement method. It is assumed that little, if any, gas remains in the coal cuttings at the end of the desorption period; therefore, no provision is made for determining residual gas. Due to the speed of gas desorption from the coal cuttings, final results are generally obtainable in one week.

Application of the Smith and Williams method is based on a calculated surface time ratio (STR) and lost time ratio (LTR) defined as

$$\mathrm{STR} = (T_\mathrm{S} - T_\mathrm{D})/T_\mathrm{S},$$

and

$$\mathrm{LTR} = T_\mathrm{S}/T_{25\%},$$

where T_D is the time from coalbed penetration to the sample surfacing, T_S the time from coalbed penetration to the container sealing, and $T_{25\%}$ the time from coalbed penetration to the time when 25% of the measured gas volume has desorbed.

A volumetric correction factor (N) is then determined from a set of STR curves and the calculated LTR. The total gas content (Q_t), including lost gas (Q_l), is then

$$Q_\mathrm{t} = NQ_\mathrm{d},$$

where Q_d is the total measured gas volume. The lost gas (Q_l) is then

$$Q_\mathrm{l} = Q_\mathrm{t} - Q_\mathrm{d}.$$

Several comprehensive studies of gas content measurement techniques indicated that problems were associated with using the Smith and Williams method for core samples. Mavor et al. (1994) and McLennan et al. (1995) indicated that when compared to pressure core gas content data, the USBM direct method provided closer agreement than the Smith and Williams method and other selected gas content methods. It should be noted that most of the comparisons by Mavor et al. (1994) and McLennan et al. (1995) were based on data from relatively deep coalbeds from a coal basin in the western United States. Under different reservoir conditions, the Smith and Williams method may provide more reliable data.

5.5. Decline curve methods

The use of oil industry decline curve analysis to estimate gas volumes desorbable from exploratory coal core samples or recoverable from coalbed gas reservoirs was first proposed by Chase (1979). His method eliminated the need for determining the residual gas, since true residual gas would not be expected to impact a mining operation or be produced by degasification. Thus only the lost and desorbed gas components of the total gas content are estimated. Decline curves applied in this manner are a tool to predict future desorption performance of a sample without the need for many months of actual desorption measurements.

Chase's decline curve method consisted of plotting gas release rate (cm^3/g per week) versus cumulative volume desorbed (cm^3) on semilog paper to produce a linear trend with least-squares regression analysis (Fig. 5). The periodic STP corrected desorption volumes were determined by a water displacement method similar to that used in the USBM direct method. The lost-gas volume (Q_l) was estimated in the same manner as that used for the USBM direct method.

The volume of desorbable gas is estimated from the decline curve (Fig. 5) by choosing an arbitrary desorption rate of 0.001 cm^3/g per day (average of 0.007 cm^3/g per week) to approximate complete desorption. This is a substantially lower desorption rate than the cutoff of 0.05 cm^3/g per day for five consecutive days proposed by McCulloch et al. (1975). Projection of the 0.007 cm^3/g per week desorption rate to the regression line constructed from the measured desorption values (Fig. 5), yields the predicted desorbed gas volume (Q_p) in cm^3 on the x-axis. The total desorbable gas volume (Q_d) is then

$$Q_\mathrm{d} = Q_\mathrm{l} + Q_\mathrm{p}.$$

A variation of the decline curve concept estimates the lost gas of a sample instead of the predicted desorbable gas volume described by Chase (1979). The Raven Ridge modified decline curve method (J.C. Huddleston, pers. commun., 1996) for estimating

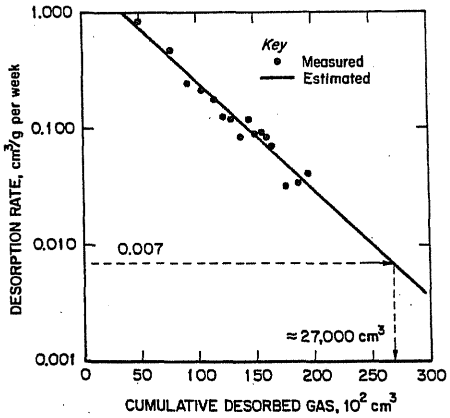

Fig. 5. Decline curve graph for estimating the volume of desorbable gas. Modified after Chase (1979).

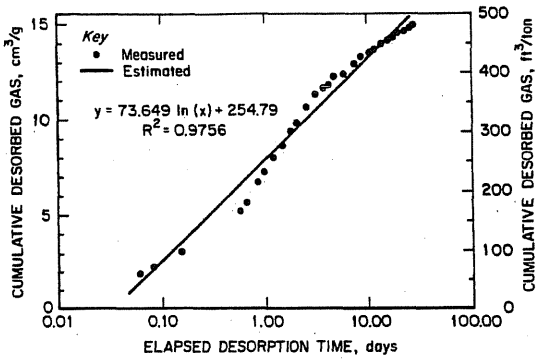

Fig. 6. Decline curve graph for estimating volume of lost gas. Modified after J.C. Huddleston, pers. commun. (1996).

lost gas utilizes all of the available desorption data, instead of only a few early points, to extrapolate back to time zero (initial penetration of the coalbed) when desorption first began (Fig. 6). This methodology is used for both cores and drill cuttings. The STP corrected desorption volumes are determined by a water displacement technique. Desorption measurements are discontinued after three consecutive daily readings of zero desorbed gas. The decline curve is a plot of cumulative desorbed gas versus elapsed time, described by a logarithmic least squares regression equation. In the example given in Fig. 6, the estimated lost-gas volume for the lost-gas time of $x = 0.0153$ days (22 minutes) would be 1.7 cm^3/g. A similar nonlinear curve fitting methodology has been proposed by Amoco Production Co. to estimate lost gas from measured desorption volumes (Yee et al., 1993). Time zero for the Amoco method is defined as when the core barrel is lifted off bottom.

5.6. Gas Research Institute (GRI) method

The gas content determination method developed as part of the GRI coalbed methane research effort (Mavor et al., 1994; Mavor et al., 1995; McLennan et al., 1995; Mavor and Pratt, 1996) is an enhanced version of the USBM direct method. The GRI Method measures desorbed gas volumes by a water displacement method using an apparatus and associated equipment significantly more complicated than the examples shown in Fig. 3.

The primary departure from the USBM direct method is associated with the estimation of lost gas. A comprehensive analysis by Mavor and Pratt (1996) of the errors associated with the most widely used gas content measurement techniques indicated that the greatest cause of error was due to conducting the tests at ambient temperature, which resulted in underestimation of lost gas. This occurs due to reduced desorption rates at ambient surface temperatures that are lower than the reservoir conditions at which desorption was initiated in the borehole. Thus, the actual volume of gas lost from a sample initially at a high reservoir temperature may be underestimated from ambient desorption readings, even when the readings are corrected to STP conditions. To compensate for lost gas estimation errors associated with extrapolating desorption data points measured at ambient surface conditions to time zero at a higher reservoir temperature, the GRI method only extrapolates those desorption data points measured after the sample is stabilized to reservoir temperature in a heated water bath.

The other suggested improvement in estimating lost gas is in the calculation of time zero. McLennan et al. (1995) defined time zero as the actual time during sample retrieval when the hydrostatic pressure of the drilling fluid was equal to the reservoir pressure. The USBM direct method estimates time zero to be the point when, in a water filled hole, the sample is half way to the surface. The GRI time zero assumption is a more accurate representation of the desorption history of coal sample during retrieval, and will generally result in a larger lost gas volume estimate. It does, however, require a measure of the reservoir pressure, and an approximation of the pressure history of the sample as it is retrieved from the borehole. McLennan et al. (1995) present several practical alternatives for obtaining a pressure history during sample retrieval.

The error analysis by Mavor and Pratt (1996) was based on several suites of samples collected from the San Juan basin of Colorado and New Mexico and the Piceance basin of Colorado in the United States. Benchmark values for error analysis were obtained from pressure core gas content data and isotherm data. It should be noted that most of the samples were from a single coal interval (Fruitland Formation) and were generally from depths greater than 600 m (2,000 ft), with extended lost gas times. Lost gas errors of the magnitude reported by Mavor and Pratt (1996) may not be typical for other coal intervals. They also would be less for coalbeds occurring at shallower depths or at lower geothermal gradient, where the difference between reservoir temperature and surface temperature would be less than that of the studied sample suite.

5.7. *Australian Standard® method*

The Standards Association of Australia (1991) has recommended a gas content test procedure based on the USBM direct method. The Australian Standard® addresses equipment construction, sampling and testing procedures, and methods of calculating the final gas content results. The procedure is recommended for core or lump coal samples with a mass of at least 500 g. Two water displacement apparatuses are recommended for determining desorbed gas volumes. The preferred apparatus (Fig. 7) consists of one or more connected graduated cylinders into which the desorbing gas is allowed to free flow. Since this apparatus does not have a separate water reservoir for equalizing water levels to directly compensate for the differential head effect, a data correction procedure is provided.

One unique recommendation provided as part of the Australian Standard® is that if CO_2 is expected to be present in the desorbed gas, an acidified brine solution should be used in the gas volume measurement apparatus to prevent the CO_2 from going into solution in the water. However, Saghafi et al. (1995) believe that the acidified brine solution only prevents the formation of the carbonate ion and has little impact on CO_2 solubility.

The lost gas (Q_1) is determined in the same manner as that for the USBM direct method (Fig. 2). Time zero is defined as the point when the sample is halfway out of the hole. The measurable gas (Q_2) is determined in the laboratory using the apparatus

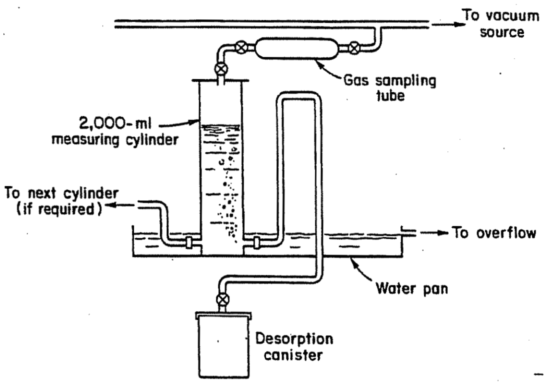

Fig. 7. Australian Standard® method gas volume measurement apparatus (Standards Association of Australia, 1991).

shown in Fig. 7. If the desorption rate is sufficiently low, the desorbing gas is allowed to free flow into the graduated cylinder. A series of water filled cylinders can be connected so that as one cylinder is filled with gas, additional gas is transferred to the next cylinder. Provisions are made in the apparatus to obtain gas samples for compositional analysis. The measurement of desorbed gas volumes is discontinued when there is no observed change in the gas quantity for one week or when the desorption curve approaches an asymptotic value. A portion of the coal sample is analyzed for ash content and relative density by standard laboratory procedures.

If desired, a portion of the coal sample is crushed in a ball mill to determine the residual gas content (Q_3). A minimum of three representative small samples (10 to 15 g) are crushed and the results averaged to determine the residual gas content.

The desorbable gas content (Q_D) is defined as

$$Q_D = Q_1 + Q_2,$$

and the total desorbable gas content (Q_{TD}) is defined as

$$Q_{TD} = \text{average } Q_3 + (Q_1 + Q_2).$$

5.8. CSIRO-CET quick desorption method

CSIRO-CET has proposed a quick-crushing gas content determination technique, which Saghafi et al. (1995) reported is commonly used in Australia in addition to the Australian Standard®. This methodology is applied primarily to core samples collected from underground boreholes. One advantage that Saghafi et al. (1995) point out is that the quick-crushing method minimizes the volume of water-soluble gases, such as CO_2, that are lost to the water column when a water displacement technique is used to measure a large number of desorbed gas volumes over an extended period.

The coal sample is placed in a desorption canister containing stainless steel balls for subsequent crushing of the sample in the laboratory without having to transfer the sample to another container. The lost gas (Q_1) is determined by the USBM method (Fig.

2) utilizing free flow desorption data points measured by the apparatus previously described for the Australian Standard®. However, to minimize problems with the loss of CO_2 to the water column, these early desorption measurements are limited to 30 min of elapsed time.

The quantity Q_1 is determined by dividing the lost gas volume (Q_1) and the desorbed gas measured in the field by the air-dried mass of the sample in the desorption canister. The volume of gas desorbed during transport (Q_2) and the subsequent volume of gas released by crushing (Q_3) are determined in the laboratory using the water displacement apparatus. The total gas content (Q_T) is then

$$Q_T = Q_1 + Q_2 + Q_3.$$

6. Reporting of results

Historically, gas content data have been reported on various bases, and in many cases, without any defined basis. All volumetric readings should be corrected to standard temperature and pressure (STP) conditions. Gas industry convention for STP conditions, 15.6°C and 760 mm Hg (60° F and 14.70 psia), are most commonly used for reporting coalbed gas content data. However, chemistry STP conditions, 0°C and 760 mm Hg (32°F and 14.70 psia), are occasionally used. The STP conditions applied to a particular data set should be clearly defined. The methodology and type of coal sample tested (core versus drill cuttings) should also be specified.

The coal compositional basis for the gas content values is another important data-reporting issue. Raw (as-received) gas content results are commonly corrected to an ash-free value to aid in the comparison of results on a normalized basis. While an ash-free basis for reporting gas content values is desirable from a standpoint of comparing results, it can lead to confusion when calculating gas resource estimates. Gas resource calculations should always be made with gas content values and coal resource data corrected to the same basis (Levine, 1991, Scott et al., 1995). Ash-free gas content values should not be applied directly to raw tons of coal in place for calculation of gas resources because an inflated value for the gas resource results.

Calculation of gas content on a volume-to-mass (weight) ratio (i.e., cm^3/g (ft^3/st)) is inherited from the mining industry where coal reserves are calculated on a weight basis. As an alternative to expressing gas content values as a volume-to-mass ratio, they can be expressed as a volume-to-volume ratio (i.e., m^3 of gas/m^3 of sample) (Levine, 1991). This volumetric expression of gas content values has been used effectively in the calculation of gas in place for studies related to longwall gob gas, where the gas is contained not only in coalbeds, but also in other rock types for which a volume-to-mass ratio has little meaning, and is awkward for gas in place calculations (Diamond et al., 1992)

Several other types of information should be provided to enhance the use and interpretation of reported gas content values. The depth of the sample should be included for each individual gas content value. If data from multiple samples from a single coalbed are combined for a single gas content value, they should be normalized by mass or volume, as opposed to calculating a simple arithmetic average (Levine, 1991). If any shale partings were excluded from the sample(s) sealed into the desorption canister(s) that should be indicated on any stratigraphic sections or for stated coalbed thickness values associated with the gas content values. It is also helpful to include either an inferred coal rank calculated from a coal proximate analysis and Btu data (ASTM, 1977) or a coal rank estimated from vitrinite reflectance measurements. Finally, any extenuating circumstance in the collection of the sample or its location relative to outcrop or mining that could have a bearing on the interpretation of the results should be noted.

7. Summary

The coalbed gas content determination methods reviewed in this paper require varying levels of equipment sophistication, auxiliary test data and data reduction complexity to arrive at a final gas content value. Selection of a method should be determined by the particular application of the gas content data and the degree of accuracy required. For mining applications where the data are to be used for estimation of emission rates, as is common outside the United States, the various quick-crushing methods are generally sufficient.

For general purpose applications, the original USBM direct method and its water displacement based variants are a good choice. These methods should include the generally accepted data correction factors (STP, differential water heads, and head space), as well as periodic gas compositional analyses. One important operational practice to increase the accuracy of gas content testing methods, especially for low gas content samples, is to fill the canisters as completely as possible with coal to minimize problems associated with a large free space. Conducting desorption testing at reservoir temperature may also be appropriate for samples retrieved from coalbeds with reservoir temperatures that are judged by those utilizing the data, to be significantly above ambient laboratory conditions.

The USBM modified direct method provides a significant level of increased accuracy and sophistication, and eliminates the logistical and technical problems associated with the water displacement techniques. Complicated and cumbersome apparatuses with fragile glassware are not required for measuring desorbed gas volumes. The MDM eliminates the problem of losing water soluble gases to the water column in the manometric devices, does not require an apparatus to correct for differential water heads, and the head space effect is directly compensated for in the test methodology.

It is recognized that cost is a consideration when selecting a gas content testing methodology. The quick-crushing gas content testing methods are generally at the low end of the cost scale; however, a determination of the true residual gas content is lost. This may not be a serious limitation for the traditional mining applications of these methods or for coalbeds where the residual gas contents have been shown to be relatively low.

The original USBM direct method and similar water displacement methods are also a relatively low-cost choice, even with the inclusion of the basic correction factors. The USBM modified direct method has a higher initial cost for equipment than most of the traditional water displacement based techniques, and the increased level of accuracy may not be necessary for some data applications. However, for large scale sampling programs, the higher initial equipment costs can be amortized over a large number of samples and several years of operation. Conducting desorption testing at reservoir temperature and utilizing the GRI procedure for estimating time zero based on actual reservoir and fluid pressure in the borehole may significantly increase the accuracy of the lost gas estimate under some circumstances, but the added cost may not be justified or necessary for all sampling situations.

No single technique is necessarily appropriate for all applications for which coalbed gas content data are utilized. It is up to the user to select the methodology that best addresses the intended application of the data at an acceptable level of accuracy and cost. In some cases, it may be appropriate to select individual components from multiple methods to meet one's needs (e.g., using the USBM MDM apparatus and general methodology, but utilizing the modified decline curve method for estimating the lost gas volume and the GRI pressure calculation to define time zero). It should be noted that the method of gas content determination can effect the quantity of each of the component parts. This can be a highly significant variable in comparing results determined by differing methodologies.

No matter which gas content determination method is used, applying good experimental method and practices is essential to maximize the inherent accuracy of any test procedure. Adhering to the reporting guidelines for gas content data will enhance the value of the results while minimizing the potential for erroneous conclusions or use of the data.

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