

Gas Reservoir Properties for Mine Gas Emission Assessment

R.J. Williams¹, D.A. Casey², E. Yurakov³

Abstract

The main aims of this paper are to provide:

- A snap shot of what we believe are the most important gas related determinations the exploration or mine geologist needs to address.
- An understanding of how these determinations fit into the broader scheme of gas emission evaluation and control.

An almost universal aim in evaluating an area is to define the quantity of gas present and those parameters that will determine its rate of migration. The main gas reservoir parameters and their interaction are broadly explained (gas content, gas composition, desorption rate, gas sorption capacity, pore pressure, permeability, relative permeability, porosity and compressibility).

The paper provides tips for gas content test sampling and evaluation of gas content data using the “gas domain” approach.

How these parameters are used as inputs into mine gas emission modelling is briefly described.

Introduction

Requirements to define gas reservoir properties for assessment of mine gas emission are increasing. In 1997, only one underground mine practiced gas drainage in the Bowen Basin. In 2000, four underground mines have adopted gas drainage. By 2005 this is expected to increase to nine underground mines.

The sensitivity of mining to gas emission is rising with planned production rates in excess of 6 million tonnes per annum, increasing gate-road lengths (> 4 km), wider longwall faces (to 350 m), thick seam mining and higher gas content coal. The burden on mine ventilation correspondingly increases with finite limits on intake/return pressures and pressure differentials across goaves for control of spontaneous combustion, delivering sufficient air to development faces for auxiliary fan compliance and increasing mine resistance. Resulting excess gas emissions can then only be controlled through gas drainage and gas capture techniques.

In designing and budgeting for borehole test programs, the exploration and mine geologist has a huge task in considering all the requirements that need to be addressed in his drilling program. With increased pressure on budgets, careful consideration needs to be given to the type of data collected and when it is collected.

¹ Managing Director, GeoGAS Systems Pty. Ltd.

² Managing Director, Multiphase Technologies Pty. Ltd.

³ Gas Reservoir Engineer, GeoGAS Systems Pty. Ltd.

Over the past four years in particular, GeoGAS and Multiphase Technologies have carried out extensive gas reservoir assessments and down stream gas emission modelling. While a lot has been learned during this time, new approaches and facts continue to emerge increasing our understanding of the deposits and the key requirements for data collection and processing.

The main aims of this paper are to provide:

- A snap shot of what we believe are the most important gas related determinations the exploration or mine geologist needs to address.
- An understanding of how these determinations fit into the broader scheme of gas emission evaluation and control.

Gas Reservoir Properties

Parameters List

An almost universal aim in evaluating an area is to define the quantity of gas present and those parameters that will determine its rate of migration. The main gas reservoir parameters are:

- Gas content
- Gas composition
- Desorption rate
- Gas sorption capacity
- Pore pressure
- Permeability
- Relative permeability
- Porosity
- Compressibility

Gas Content

Measurement

Gas content is one of the most fundamental measurements describing the gas reservoir. It is a static measure of the quantity of gases contained in a given mass of material, and is normally measured in three stages:

- Initial desorption in the field to determine the quantity of gas lost before sealing the core in the gas canister. The calculated quantity of lost gas per unit mass of coal is termed “Q1”.
- The gas volume desorbed from the intact bore core per unit mass of coal, prior to removal of the core for crushing is termed “Q2”.
- The gas volume released during crushing per unit mass of coal is termed “Q3”.

In the terminology prior to release (in October 1999) of the updated guide for gas content determination by Standards Australia, Total Desorbable Gas Content (Q_{TD}) is

the sum of Q1+Q2+Q3. In the current guideline (AS3980-1999), the term Q_{TD} has been replaced by Measured Gas Content (Q_m , Table 1).

Table 1 Main Differences Between the 1991 and 1999 Gas Content Standards

Item	AS3980-1991	AS3980-1999
Terminology	Total Desorbable Gas Content (Q_{TD})	Measured Gas Content (Q_m)
Reporting T&P	STP (0°C and 1013 hPa)	20°C and 1013 hPa
Q3 determination	Optional	“Should be determined”
Fast desorption method	Not included	Included
>20% CO ₂ in seam gas		Should use fast desorption method.

Gas content is measured either directly or indirectly. Direct testing measures the actual quantity of gas in the bore core. Use of equations to calculate gas content from other parameters (eg depth, ash) is an example of an indirect method of determination. Two types of direct measurement are used:

- Slow desorption
- Fast Desorption

The fast desorption method only varies from the slow desorption method in the time allowed for Q2 desorption. Instead of waiting up to 100 days for Q2 desorption to be completed, the core is taken “off line” and crushed to immediately release the remaining gas. In slow desorption testing, Q2 is normally the largest gas component, with Q3 being small. In fast desorption testing, Q3 is usually the largest gas component.

Unless there is only one seam gas component, gas composition is as important as gas content to measure. The slow desorption method is unsuitable where CO₂ is present due to difficulties in preventing solution of CO₂ in the water bath of the test equipment. Both methods can produce large proportions of air free N₂, resulting from oxidation of the core in the gas canister and crushing mill.

Apart from the test method, the gas content magnitude is mostly affected by:

- Mineral matter content, where gas only desorbs from carbonaceous material. Inclusion of stony material that produces essentially no gas, results in a reduced gas content. The inclusion of this material is valid provided the mineral matter content for the whole sample is defined as either ash % or relative density.
- Sampling bias in the laboratory, where a heterogeneous core is sub-sampled for Q3 testing. This problem is greatest with the fast desorption method, when a dual coal quality/gas requirement exists for the core. The amount of sampling bias is related to the allowable sample size and the degree to which the core can be mixed for sub sampling. It is preferred procedure to use cores dedicated to gas content testing.

An essential requirement for every exploration-related gas content test is that the ash and/or relative density (RD) of the material tested be defined.

Gas Domains

The Gas Domain approach facilitates:

- An understanding of the geological controls.
- Definition of the gas reservoir size for a minimum number of tests.
- For each domain, quantification of the gas content variability facilitates down-stream sensitivity analyses/probability calculations of required outputs.

The gas domain approach was first applied in 1997 at Central Colliery. It has since evolved over its application to 12 mines or areas in the Sydney and Bowen Basins.

In the course of evaluating gas content distributions, it became apparent that mappable areas could be resolved where the change in gas content with depth (for example) could be differentiated from adjacent areas. Boundaries between these areas are normally quite sharp and well defined and would appear to have some geologic control.

Gas domains are therefore defined as areas where the gas content magnitude varies according to a set of defined conditions, ie gas content for the domain is a function of say depth and ash and the variability is tight enough to distinguish it from other domains and be useful.

The extent to which gas domains can be resolved depends upon the ability to reduce the noise created by the mineral matter, test and sampling inconsistencies and combining results from different laboratories. It also follows that the most cost efficient means of defining the gas environment over an area is one where these noise effects are minimised.

An approach toward resolving gas domains, defining equations describing the gas content in each domain and quantifying and minimising the level of uncertainty involves:

- Identifying samples suspected of error.
- Rating the sample test reliability.
- Correcting the gas content for mineral matter (ie correct all values to a common ash or RD).
- Create charts of mineral matter corrected gas content against depth. Examine the data set and determine if different fields are resolvable. If so, calculate the standard deviation about each resolved field.
- Plot the “resolved field” data on plan. Almost invariably, discrete areas or gas domains will be identified.

The main approach to being more confident about the data is to evaluate its internal consistency. A single sub sample from a seam intersection is difficult to evaluate. The confidence of single sub sample tests is enhanced if they fit reasonably well into a

regional pattern. Consistency between multiple sub samples produces a much higher level of confidence.

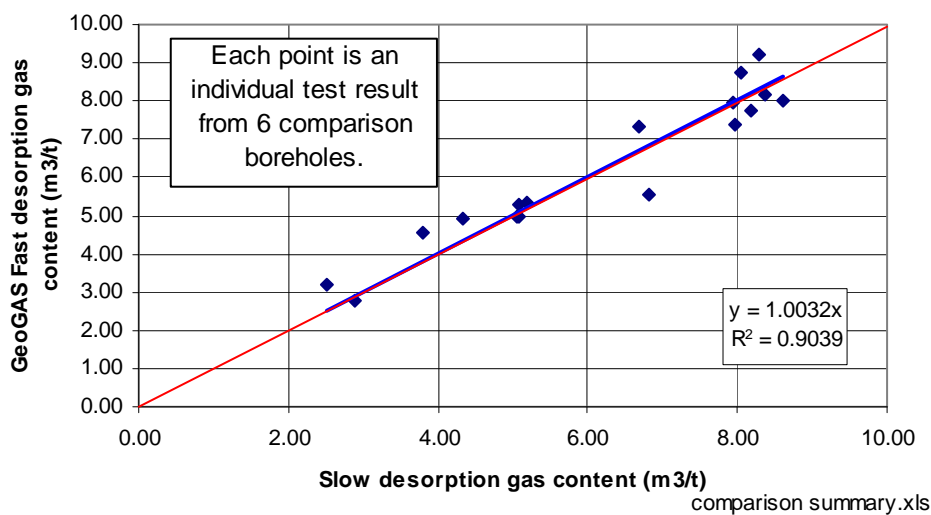
Therefore, regardless of how well an individual test has been carried out, consistency between sub sample tests carries a lot of weight.

Rather than reject apparently poor data (that may in the fullness of time, be shown to be valid), it is better to include all the data, but provide a reliability rating. It is then incumbent on the user to decide what is applicable in his or her context.

The following ratings provide an example of what has been applied to the Goonyella Middle seam areas. Because GeoGAS tests are widely used in the coal industry, other laboratories tests are rated on the confidence of their alignment with GeoGAS⁴. To qualify for “alignment” the non-GeoGAS tests would have to undergo direct comparison testing via core redrills/wedging or alternate sub-sampling of the seam section.

Direct comparison tests of GeoGAS fast desorption against other laboratories⁵ slow desorption have been undertaken on a number of occasions (Figure 1). The almost perfect correspondence between the fast and slow desorption tests is to some extent fortunate, as selection of sample mass size for Q3 testing affects the final result due to its effect on the equilibrium partial pressures.

Figure 1 Comparison Fast and Slow Desorption Results for Dominant CH₄ Coals Tested 1997 to 1999



The highest confidence is given to multiple sub-samples from a single seam intersection that has low standard deviations after ash correction.

⁴ This was a convention for this study. It is not an assertion that GeoGAS tests are any closer to the absolute true result, than any other laboratory.

⁵ McElroy Bryan Geological Services, Energy Minerals Pty. Ltd., Earth Data Pty. Ltd., Capcoal

Highest Confidence

1A > 2 samples, ash corrected standard deviation <1, direct test comparison in alignment to GeoGAS.

1B 2 samples, ash corrected standard deviation <1, direct test comparison in alignment to GeoGAS

2A 2 or more samples, ash corrected standard deviation <1 and (as applicable) normal slow desorption curve, but uncertainty in tie to GeoGAS.

2B ash corrected standard deviation <1, but slow desorption curve showing signs of leaking (no clear asymptote).

3A Single sample, result otherwise valid but no consistency check, multiple samples ash corrected standard deviation ≥ 1 but no errors apparent.

3B Single sample slow desorption test with curve extrapolated to asymptote

4 - Highly irregular desorption curve/s, established leakage (normally rejected data).



Least Confidence

Gas Reservoir Size

Gas content on its own can be a poor indicator of seam gassiness, and in the past, low gas content values have been mistakenly used to assume low gas emission. The gas reservoir size gives a much better indication of the amount of gas in place by accounting for mineral matter variations and seam thickness.

It is best expressed in terms of m^3 of gas per m^2 of seam floor area.

$$\text{Reservoir size (m}^3/\text{m}^2) = Q \cdot D \cdot L$$

Where

Q = Measured gas content ($Q_m \text{ m}^3/\text{t}$)

D = Relative density (t/m^3)

L = Seam thickness (m)

In Table 2, the same gas reservoir size is defined for gas contents differing by a 3 x magnitude.

Table 2 How Different Gas Contents Result in Similar Gas Reservoir Sizes

Qm (m^3/t)	RD (g/cc)	Seam Thickness (m)	Gas Reservoir Size (m^3/m^2)
Q	D	L	$Q \cdot D \cdot L$
5	1.44	8	57.6
15	1.3	3	58.5

While the gas reservoir size is similar in Table 2, the gas emission response will be quite different due to the higher desorption pressure of the high gas content sample. However, if the low gas content sample is taken from low rank, low storage capacity coal, its desorption pressure could be much higher. Here we need to consider the effect of gas sorption isotherms and permeability, which are discussed later.

Desorption Rate

The rate at which gas desorbs from the coal matrix is defined by a number of indices:

- **Desorption Time Constant (Tau)** - The time taken in days for 63% of the gas to have desorbed from intact bore core during a slow desorption test.
- **Initial Desorption Rate (IDR30)** - A measure of the rate of desorption from intact bore core in the first 30 minutes after coring. The index is calculated by dividing the quantity of gas given off in the first 30 minutes after coring, by the sample mass. While it is a standard GeoGAS measure, it can be calculated from all laboratory tests.
- **GeoGAS Desorption Rate Index (DRI)** - A measure of the rate of gas desorption during crushing of the coal sample, corrected to the Qm of the sample. (The gas volume generated after 30 seconds of crushing a 200 g sample corrected from the “Gas on Crushing” value to the Qm value). This index is specific to GeoGAS apparatus.

Tau is used as an input parameter for the gas reservoir simulator “SIMED” (discussed later). Fast desorption measurements do not measure **tau** directly. It is currently calculated from the **IDR30** index according to:

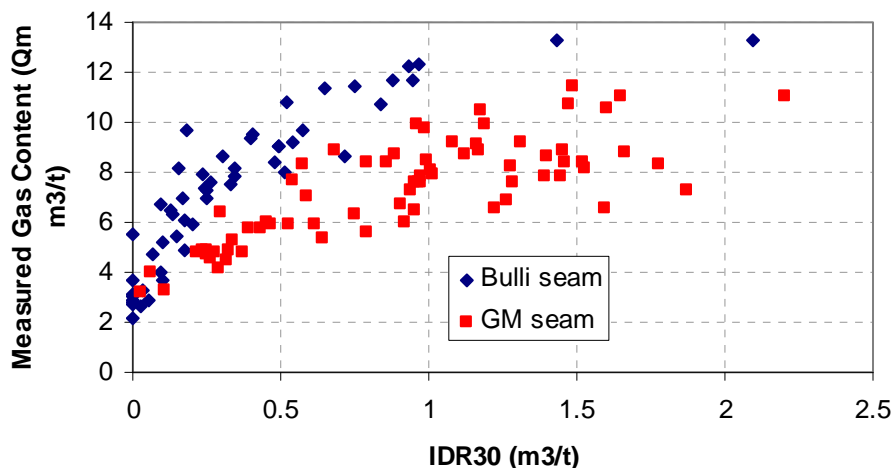
$$\mathbf{Tau} = 4.82 \times \mathbf{IDR30}^{-0.70}$$

Desorption rate is sensitive to:

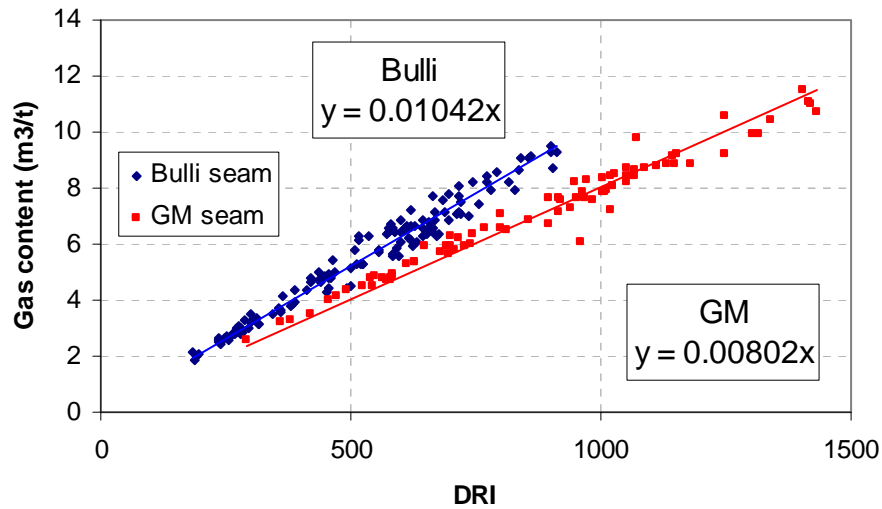
- Gas content magnitude
- Gas composition
- Particle size
- Moisture
- Inherent coal structure

Bowen Basin coals (Goonyella Middle seam, Goonyella Lower seam, Burton seam, Girrah seam, German Creek seam) typically exhibit faster rates of gas desorption compared to NSW South Coast coals (Bulli seam Figures 2, 3).

**Figure 2 IDR30 Desorption Rate Comparison
Goonyella Middle and Bulli Seams**



**Figure 3 Desorption Rate During Coal Crushing
Goonyella Middle and Bulli Seams**



The DRI value of 900 is used to set gas content threshold limits for outburst proneness (Williams, 1997). In the example given above, the threshold DRI for the Goonyella Middle seam occurs at 7.3 m³/t compared to 9.4 m³/t for the Bulli seam.

Gas Storage

Gases are adsorbed onto coal micro-pores and held in place by water pressure. The amount of gas that can be adsorbed for a given pressure is defined by the gas sorption isotherm, where the relationship between pressure and adsorbed gas is given by the Langmuir equation:

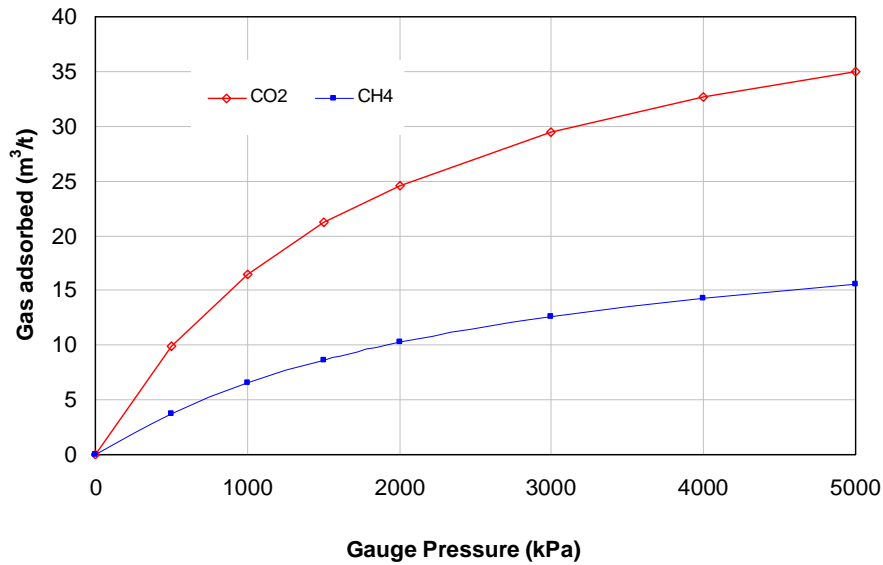
$$V = \frac{a \cdot P}{P + b}$$

where: V – Volume of gas adsorbed (m³/t)
 P – Absolute or the gauge pressure (kPa)
 a - Langmuir volume (m³/t)
 b - Langmuir pressure (kPa)

Coefficient a (Langmuir volume) represents the maximum amount of gas, of a particular type that will be absorbed on the surface of the coal. Coefficient b (Langmuir pressure) represents the pressure at which half the gas of a particular type that can adsorb on the surface of the coal will be adsorbed.

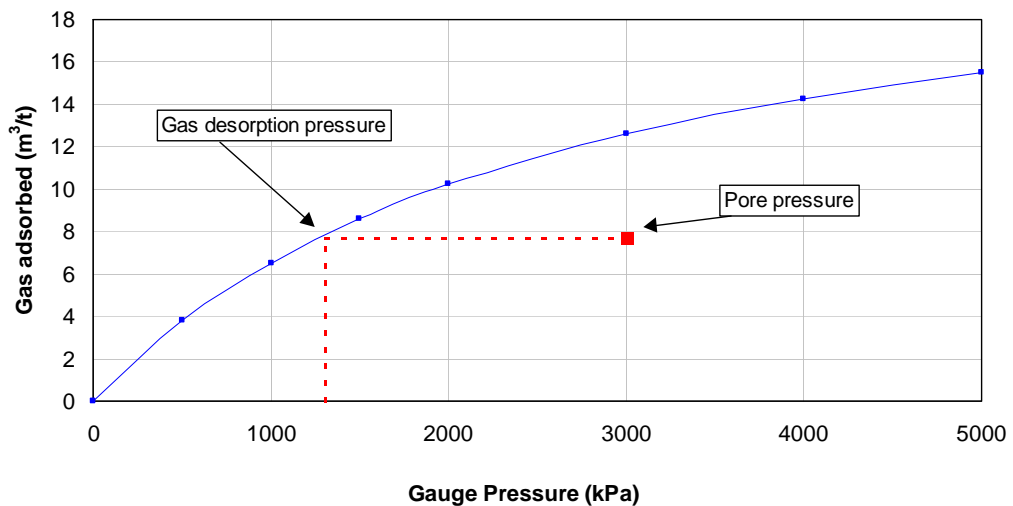
CO₂ has at least double the adsorption capacity of CH₄ (Figure 4). Other factors significantly affecting the nature of the isotherm are temperature and mineral matter content.

Figure 4 Example Gas Sorption Isotherms



Pore pressure is the pressure of fluid in the pore volume. When the pore volume is 100% saturated, the pore pressure is equal to the pressure of the head of water. The pore pressure, gas content and sorption are all directly measured. In the example in Figure 5, the virgin conditions show a gas content of 7.7 m³/t and the pore pressure of 3000 kPa. When the gas content value plots below the sorption isotherm curve, the coal is *under-saturated* with respect to gas. For gas desorption to occur, the head of water needs to be drawn down to 1310 kPa. This is the *gas desorption pressure* for that particular gas content and isotherm.

Figure 5 Example Gas Desorption Pressure



SIMED modelling has shown the gas emission responses to be highly sensitive to the degree of saturation (combined effect of gas content and nature of the isotherm). A situation where the gas content distribution is well defined, but the sorption isotherm is poorly known, results in a low level of certainty in emission modelling out put.

Gas Transport

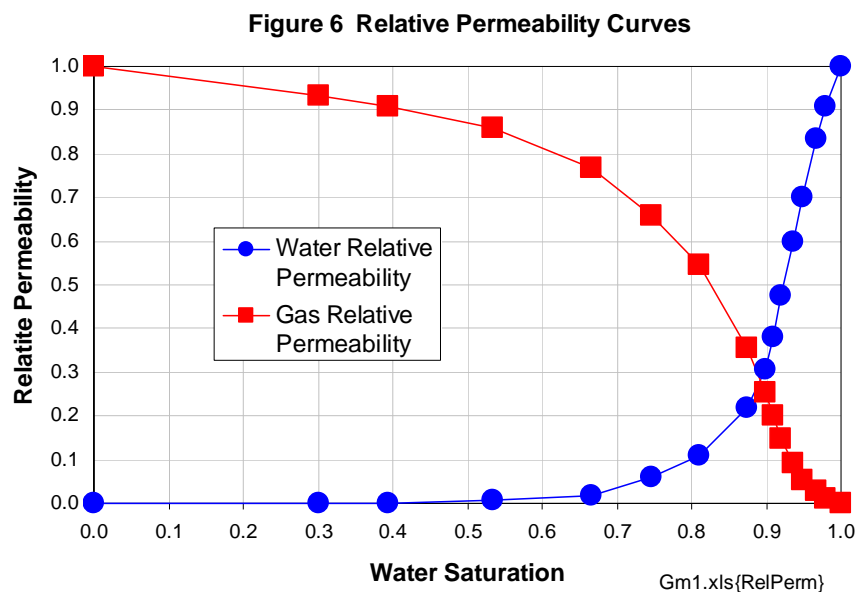
One of the main determinants of the rate of gas migration through coal is permeability. It is one of the more difficult parameters to characterise because coal seams are heterogeneous, fractured reservoirs. It is a measure of the ability of a porous rock to transmit fluid.

Absolute permeability is a property of the solid, not the fluids, and has units of area.

It is defined in Darcy's Law, which relates fluid flow q through a cross sectional area A to the permeability of the media, viscosity of the fluid and the pressure gradient.

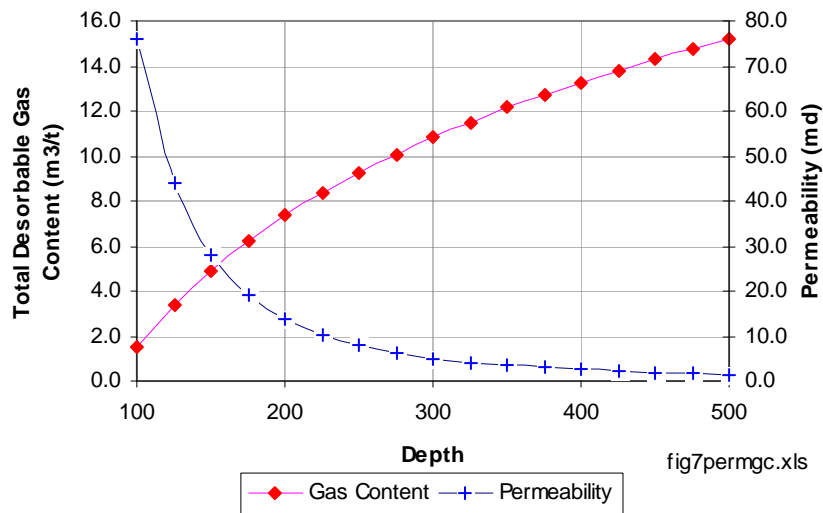
If more than one fluid is present, each fluid experiences an effective permeability. The ratio of the effective permeability to the absolute permeability is the relative permeability for that fluid.

Relative permeability curves describe the interference that gas has on water flow and water has on gas flow. Relative permeability curves of gas and water are a function of water saturation in the pore volume (Figure 6).



Permeability is normally stress dependent. With increasing depth, permeability normally reduces but gas content increases. Typically for Bowen Basin mines, as workings progress from shallow areas to deeper areas, they pass from high permeability, low gas content coal to lower permeability higher gas content coal (Figure 7).

Figure 7 Example of Cross Over of Permeability and Gas Content With Depth



Permeability frequently exhibits directional characteristics, in response to cleating and stress directions. Measurement of directional permeability from surface well tests is possible using interference tests. This involves either injecting or producing from one borehole and measuring the water level or pressure response in at least three non-co-linear monitor holes. The pressure response in the various monitor holes is a function of permeability between them and the active borehole. Therefore, the relative pressure changes can be used to characterise the orientation of the maximum and minimum permeability trends.

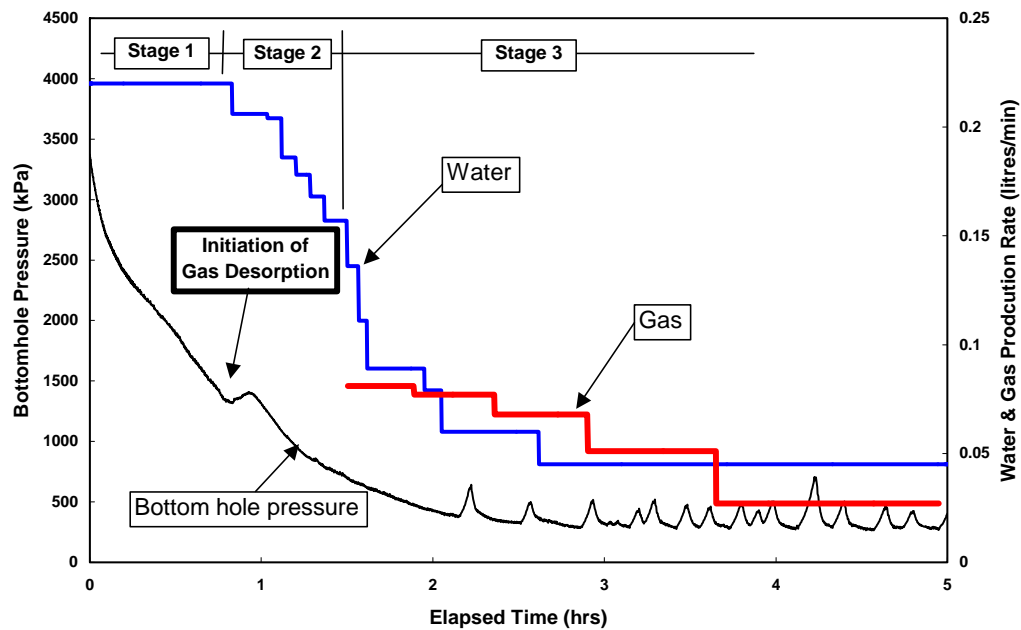
It is not uncommon for the permeability in one orientation (often, but not limited to the face cleat direction) to be in the order of 3 to 4 times higher than the other.

This will have a significant impact on both the rate and amount of water and gas flow from both in-seam and surface borehole drainage patterns. With a knowledge of the direction and degree of maximum permeability, drainage pattern sweep efficiency can be optimised by both increasing and decreasing borehole frequency in the direction of the high and low permeability orientations respectively. Similarly rib emissions may be higher in one orientation.

In addition to determining permeability anisotropy, interference testing also yields estimates of porosity/compressibility; another parameter required for gas emission modelling that is rarely measured in field studies.

Multi-phase well testing typically shows the stages of water and gas evolution that occur as the pore pressure is reduced. Pumping initially produces only water (Stage 1, Figure 8). When the pore pressure is reduced to the gas desorption pressure, a “kick” in the bottom hole pressure trace can occur. From this point on, gas is desorbing, but not yet flowing (Stage 2, Figure 8). With increasing gas desorption, the permeability to water decreases and water production declines, while the permeability to gas increases. Eventually, sufficient gas has desorbed for the bubbles to interconnect and commence flowing (Stage 3).

Figure 8 Gas and Water Production During Multi-Phase Testing



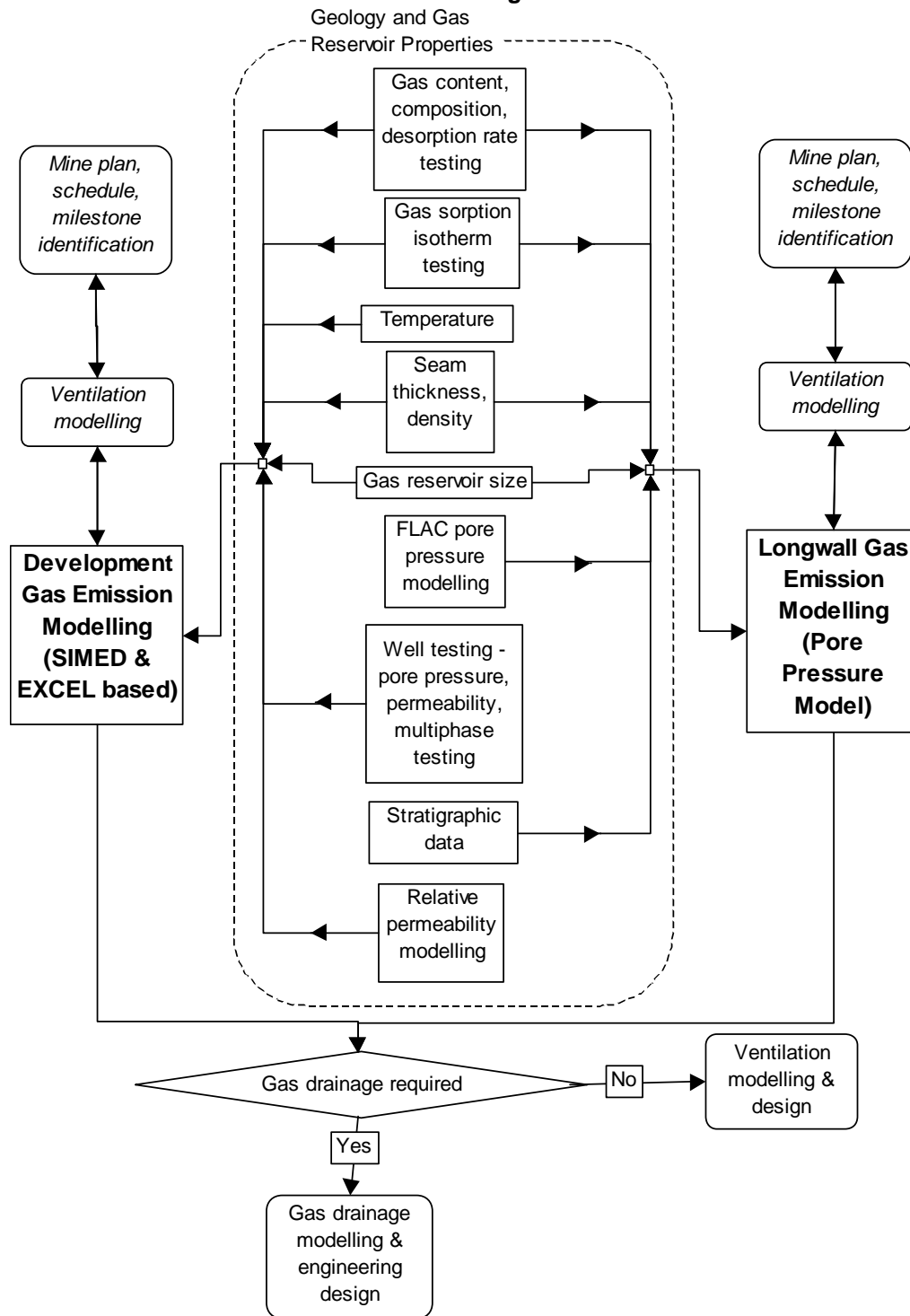
Application to Coal Mine Gas Emission Assessment

Longwall and development emission models serve to combine the inherent gas reservoir properties with mining parameters to arrive at results that can be used in mine planning (Figure 9). Development emission modelling relies heavily on the gas reservoir simulator SIMED, to define the roadway gas emission decay curves.

SIMED models the flow of gas and water in coal seams and is used to model the behaviour of surface wells, in seam boreholes and mine roadway emission. Gas and water production of surface and in seam boreholes can be history matched or predicted.

SIMED is a two phase (gas and water), three dimensional, multi-component, single or dual-porosity reservoir simulator designed to model coal seam gas reservoirs. The main modelling inputs are listed in Figure 9 as inputs to development emission modelling. The rough order of importance of these parameters is gas content, permeability, seam thickness, isotherm data, desorption time constants, relative permeability and pore pressure.

Figure 9 Basic Geology and Gas Reservoir Parameters That Input to Gas Emission Modelling



Some features of SIMED are:

- Simulation of the behaviour of coal seam gas reservoirs as single or dual-porosity⁶.

⁶ Dual porosity refers to coal, where the adsorbed gas is modelled as being contained within a secondary porosity system which has a very low permeability. The desorption time constant restricts

- Simulation of the flow of various gases and combination of gases and water within the coal seam.
- Allowance for multiple coal properties within the one simulation. The different coal types are defined by permeability, porosity and desorption isotherm parameters. This is particularly important for the dipping Bowen Basin seams, where grid elements surrounding and along a roadway need to be assigned varying gas contents, permeabilities and pore pressures according to how these parameters change with depth.
- Modelling the effect of gas emissions in underground coal mines using a grid block face drainage option which allows gas to drain to atmospheric pressure through grid block faces. If necessary face drainage can be modified during the simulation time to include continuing mine development.

The main outputs are roadway emission time-decay profiles. In themselves, these are not directly useable in mine planning. An interactive EXCEL spreadsheet is used that enables calculation of gas emission in response to the following changing mining parameters:

- Panel advance rate
- Air quantity supplied to the panel
- Air leakage defined by roadway and stoppings resistance factors and pillar length.
- Intake/Return air pressures.
- The number of headings and intake/return ventilation schemes.
- The change in gas emission with panel length.
- Selections of options covering a range reflecting levels of uncertainty in the permeability, gas content and other basic parameters.

The development emission models are typically targeted at the same panels used in ventilation milestones. Where excessive air quantities, velocities and pressures are required to reduce gas concentrations, gas drainage is required to handle the excess gas emission.

Longwall emission modelling is also typically targeted to ventilation milestones. Assessment of gas reservoir size distribution (gas quantities in the roof and floor strata) can require a ventilation milestone to be set in areas on expected highest gas emission.

GeoGAS most commonly uses the “pore pressure” model in longwall applications. It assesses gas release in the destressed zone above and below the extracted area. For the higher permeability Bowen Basin coals, the state of rib emission at the time of longwall mining needs to be also included.

The longwall gas emission model is EXCEL based and utilises a geomechanical modelling package FLAC, which models stresses, displacements, fracturing and pore pressure distribution in strata around the longwall. Longwall gas emission

the rate at which gas can move from the secondary porosity system to the primary porosity (cleat and fracture system) where pressure gradient controls the flow.

calculations are based on the gas desorption properties of coal seams and non-coal strata, the non-coal water saturation, goaf loading effects and mining production.

The model is capable of quantifying the gas make from changes in:

- Gas content of the coaly material
- Coal sorption properties, including gas desorption rate
- Porosity and water saturation of the non-coaly material
- The thickness and proximity of the gas sources to the working seam
- Longwall face width
- Gas capture and working seam predrainage
- Mining rate

The main inputs are indicated in Figure 9.

Pore pressure output from FLAC modelling is used to define regions where gas will desorb according to the gas adsorption isotherms. Gas desorption will occur when the pore pressure is reduced below the desorption pressure, which is calculated from the gas content and sorption isotherm.

Considerations for Geologists

In defining the nature of data to be collected, the suggested approach depends upon the stage of evolution in development of the deposit. Is it in the initial exploration stage, the stage before the final feasibility study or is mining already taking place?

Time permitting, a staged approach to drilling is desirable, where results from one campaign can be used to most effectively design drilling for the next campaign. In the initial exploration stage, it is normally sufficient to obtain cores for gas content testing only (with related gas composition/desorption rate testing).

The whole seam needs to be assigned a gas content value, and this can be best achieved by taking sub samples from each seam section. Where variability between coal plies is poorly understood, it is useful to sample the entire seam in say 1 m intervals. Almost always, the variability between plies will be reduced (to standard deviations of less than 1) by correcting the gas content value to a common ash or density. Correcting to an average seam ash/density is preferable to correcting results to an ash free basis. The latter run the risk of the higher gas contents being used/quoted in mining applications and unnecessarily causing angst. Depending upon the amount of carbonates in the coal, zero gas content can match an ash of anywhere between 80% and 100%.

For seams where the variability is understood (the great majority of cases), 3 sub-samples per seam intersection are sufficient.

The uniformity of gas content distribution is tested using the “gas domain” approach, with drilling in the next stage being targeted toward resolving anomalies.

For initial exploration of an area, gas content test coverage should be adequate where the gas domains have been tightly defined (eg standard deviation of less than 0.7 m³/t

with 20+ samples). It is suggested that subsequent gas content testing can be held over until a mining area has been identified.

In the more detailed drilling in proving up an area for mining, further gas content tests can be taken to confirm the more regional gas domain trends. It is at this stage where gas sorption isotherm tests, and well tests for permeability and multiphase testing should be done.

Temperature logs are required to define the geothermal gradient (for heat assessment/management issues) and the temperature at which the gas sorption isotherms are to be tested.

While there is normally adequate sampling for gas content testing, there are usually insufficient determinations made for permeability and gas sorption isotherm testing. In helping to decide how many data are enough, a useful approach is to apply probability and sensitivity modelling techniques. With probability modelling, input parameters are defined as a range (eg mean and standard deviation for normal distributions). Modelling packages such as @RISK can calculate the outputs as probability ranges and rank the inputs in terms of their contribution to the overall uncertainty. This approach can help distil clear priorities for further data collection in quite complex situations.

The level of uncertainty (risk) often dictates a trial mine approach, where from a gas view point, the more difficult determinations of permeability and directional permeability can be defined at close range, and original model outputs can be re-visited in the light of actual data obtained from trial mining.

Conclusions

Data gathering in any venture is dictated by its ultimate end use. In this paper, the application of gas testing data has been broadly described in an attempt at clarifying the context of gas data collection. From the geologist point of view, it is important to avoid overlooking important elements, especially those that can be most easily obtained in conjunction with other, committed testing.

References

Williams R.J., 1997: *Definition of outburst threshold limits from core testing* in Symp Safety in mining - role of geology, Coalfield geology council of NSW, Newcastle November 1997.