Measurements of relative permeability, absolute permeability and fracture geometry in coal

by
L. Paterson[1], K. Meaney[1] and M. Smyth[2]
[1]CSIRO Division of Geomechanics [2]CSIRO Division of Exploration Geoscience

ABSTRACT

Adequate permeability is vital to the coalbed methane industry. We report here on three issues of importance to the subject of coal permeability.

Laboratory measurements of relative permeability in Australian coal have been made in our laboratory. These experiments were conducted to provide data for numerical simulation and evaluation of coalbed methane reservoirs. Transient flow was used to determine drainage relative permeability, this having the most relevance to the primary depletion of a reservoir.

Many of the Australian coals we have tested have displayed mineralisation of the cleats and fractures. Acid leaching of these coal cores in the laboratory has led to an increase in permeability of up to two orders of magnitude.

Characteristics of coal that provide attractive permeability have been examined microscopically in cross-sections. Vitrite rich coals display the best cleat and fracture development, and vitrite-rich seams may be the best potential exploration targets.

INTRODUCTION

The discovery of coal with adequate natural permeability is arguably the most significant issue in the coalbed methane industry. Numerical studies have verified the importance of absolute and relative permeability in determining whether viable methane production rates can be achieved (Arastoopour and Chen, 1991).

Gas production is proportional to the product of the absolute permeability and the relative permeability to gas. It appears that there are at least two factors in the Sydney and Bowen basins inhibiting wide-spread discovery of commercial permeabilities. One factor is the low level of natural fracturing associated with seams containing a high percentage of inertinite, the other factor is secondary mineralisation that fills the fractures and blocks fluid flow.

In addition, knowledge of relative permeability reveals that high values of water saturation mean that relative permeability to gas is far below the permeability to fully saturated water flow. Reduction in water saturation increases relative permeability to gas, but the theoretical maximum is not even nearly reached because of high residual or connate water saturation.

It is the purpose of this paper to address these issues. We report here on laboratory measurements of absolute and relative permeability, results of acid leaching experiments with laboratory cores. Microscopic observations of natural fracturing or cleating are also described, and evidence for characteristics of exploration targets is presented.

By petroleum standards, the literature on the gas or water permeability of coal is limited. Of published work, most of it deals with the effect of stress on permeability (eg. Pomeroy and Robinson, 1967; Durucan and Edwards, 1986; Harpalani and Zhao, 1989). Relative permeability has received little attention, either due to the proprietary nature of the testing or the difficulty of obtaining useful results. Relative permeability measurements for some U.S. coals have been reported by Reznik *et al.* (1974), and very recently by Puri *et al.* (1991) and Hyman *et al.* (1991)

CORE HANDLING AND SAMPLE SELECTION

Sample selection is a major issue in laboratory testing of coal. Samples of coal for laboratory testing are biased toward strong coal types, because weak fragile coal usually disintegrates during coring or transport. Core handling and sample selection issues for US coal are discussed by Dabbous *et al.* (1974) and Hyman *et al.* (1991).

Bright bands are more highly fractured than the dull ones, which means coal containing bright bands has higher permeability, as discussed below. However, coal tends to fall apart on the bright bands, so that testing is generally performed only on the dull, low permeability bands.

In our laboratory, we have tested a variety of sizes of coal cores. The diameter of exploration holes is often a limiting constraint, otherwise it is desirable to test samples as large as possible. It is usually necessary to prepare samples with a particular orientation, due to the anisotropic permeability in coal. A common size of testing in our laboratory is with cores of length 120 mm and diameter 50 mm. The coal was stored under water wherever possible to prevent dehydration and retard oxidation. Plastic tube that shrinks after brief heating has been found useful to keep cores intact. Wherever possible we preferred to obtain large blocks, which can be cast in plaster, and stored under water, until the coal is ready to be tested.

RELATIVE PERMEABILITY MEASUREMENTS

Two methods have been in use in the petroleum industry to determine relative permeability in laboratory experiments. The steady-state technique is preferred for sandstone and carbonate samples (Hyman *et al.*, 1991). In the steady-state method, flow is established until a constant value of water saturation is obtained uniformly throughout the sample. Permeability to gas and water is then determined at that value of saturation. Then the saturation is changed, the process being repeated. However, heterogeneity and low porosity in coal pose particular problems for the accurate determination of saturation. The time taken to achieve steady-state flow is a major impediment to the implementation of such methods.

In the unsteady-state method, the core is saturated with one fluid, which is subsequently displaced with a second fluid. If gas displaces water, this is referred to as drainage, whereas water displacing gas is referred to as imbibition. A consequence of the unsteady-state method is that saturation equilibrium is never achieved. Produced volumes of both fluids are monitored and recorded as a function of time. A mathematical model is then used to derive the relative permeability curves. We used the Johnson, Bossler and Naumann (1959) method, known as the JBN method, to analyse unsteady-state displacement tests. The apparatus used for the tests is shown in Figure 1.

The JBN method is an explicit method. It is used routinely in the conventional oil industry for calculating relative permeabilities from transient displacement experiments when capillary pressure is not important (Tao and Watson, 1984). Wettability measurements on coal often give a contact angle of the gas-water interface close to 90° (see below), so capillary effects in coal should be small. Hence the use of the JBN method should be valid.

The JBN method is straightforward, not requiring an iterative procedure or a priori functional forms of the relative permeabilities. A disadvantage of the JBN method is that the derivatives of measured data must be estimated. It is well known that the effect of small measurement errors become amplified when derivatives of measured data are to be estimated. The JBN method is based on the Buckley-Leverett theory (Buckley and Leverett, 1942). This is the classic theory for core displacements.

Typical results of relative permeability measurements for a Bowen Basin coal are shown in Figure 2. Difficulties are encountered in measuring relative permeabilities when the relative permeability to water drops very low. This is because it becomes difficult to reduce the water saturation further. This results in high residual water saturations, and relative permeability to gas remains low. Results from relative permeability experiments, such as shown in Figure 2, are used in numerical simulations which forecast production and determine viability of coalbed methane developments.

ACID LEACHING

The frequent occurrence of secondary mineralisation in the Australian coal we have tested from a number of locations appears to be a significant issue. Coal which would be expected to have an attractive permeability for economic methane exploitation can have its permeability substantially reduced by mineralisation. A variety of minerals have been encountered infilling the fractures and cleats, including calcite, ankerite, siderite and illite.

We present here some results of laboratory trials with acid leaching that remove secondary mineralisation. With coal infilled with carbonates from the Hunter Valley, permeability increases of a factor of 100 have been obtained after leaching with hydrochloric acid. A typical result is shown in Figure 3. Anomalous peaks and dips in the data are attributed to the release and migration into bottlenecks of coal fines.

Field trials have not been conducted, nor have the economics been evaluated. However, the success of the laboratory trials, combined with the knowledge gained from successful acid treatment of carbonate rocks in the conventional petroleum industry are encouraging. This is obviously a topic for further investigation.

FRACTURE FORMATION

Characteristics of coal that provide attractive permeability have been examined microscopic in cross-sections. Fracture width, constrictions, coordination, connectivity, backbone paths and dead-ends are important not only for permeability but for determining the reasons for the high values of residual water saturation. To locate regions of higher permeability it is worthwhile to examine the factors that cause natural fractures to occur. Observations other than direct measurement may then become useful in locating high permeability regions.

Coal has been formed from plant debris in two stages, In the peatification stage, extensive biochemical reactions occurred, in which the mechanisms were principally determined by the accessibility of the debris to oxygen. In the geochemical coalification stage, abiotic alteration proceeded mainly by compaction, dehydration and a series of condensation reactions. Coalification is considered to be a diagenetic process up to the stage of mature brown coals. From hard brown coal rank the alteration is so severe as to be regarded as metamorphism (Stach *et al.*, 1982, p.38). Coalbed methane is formed during the coalification process.

Here we hypothesise that fractures in coal are due to shrinkage of the coal as a portion of the coal is converted to gas and water. As the coal shrinks, vertical contraction can be accommodated by a downward movement of the overburden rock. This is possible because of the vast lateral extent of coal seams. This downward movement will retard the formation of horizontal fractures.

Horizontal shrinkage, however, will not necessarily be accommodated by inward sideways movement of rock. This is because coal seams are in general thin, and the roof and floor strata, which do not shrink, will provide support to inhibit sideways contraction. Thus the coal goes into tension sideways and vertical fractures form. Generally, the horizontal stress field is anisotropic, and the fractures will form normal to the direction of minimum horizontal compressive stress.

Observation of coal shows that is composed of many horizontal layers of different composition (Smyth and Cook, 1976). The microscopic components of coal, or macerals are grouped into three major types: vitrinite, liptinite and inertinite. In the peat stage of coal formation, the plant debris which has been severely biochemically altered forms the inertinite macerals. These do not undergo further alteration to the extent of the vitrinites and liptinites. The inertinites produce the least volume of gas and their size and shape remains relatively unaltered through the coalification process. In contrast, the vitrinites, preserved from severe biochemical oxidation in the peatification stage, undergo extensive changes as coalification progresses, passing through a "gelification" phase, which leads to the somewhat homogeneous appearance of vitrinite and to a "bright" lustre. Vitrinites produce more gas than inertinites. Liptinites in Australian Permian coals rarely comprise more than 10% of a seam.

It is therefore argued that because vitrinites have produced more gas than inertinites they have consequently shrunk more. Thick layers of inertinite-rich coal, or inertites, may thus be considered as performing some of the same role as the roof and floor strata, supporting horizontal loads and transmitting vertical loads. Vitrinite-rich layers of coal, or vitrites, which macroscopically are described as "bright" coal, are expected to contain the most fractures. Indeed, direct observation of slices through coal shows that a higher degree of fracturing is in the brighter bands.

In a microscopic study of the Permian German Creek Coal from the Bowen Basin in Queensland, fractures of sizes less than 1 µm to 20 µm, and more, were clearly visible. The fractures occurred predominantly in vitrinite, especially where present in thick vitrite bands. This is consistent with the concept that fine fractures are mainly confined to vitrinite layers and are developed due to the shrinkage of the coal. The coarser fractures which cut through all microlithotypes could be due to processes external to the coal forming process, such as tectonic activity, or, simply, to the extraction of the coal.

It is a relatively simple matter to map out the positions and thicknesses of vitrite, inertite and intermediate layers in a coal seam. This may assist in the evaluation of a seam for desirable permeability characteristics. Vitrite rich coals display the best cleat and fracture development, and may be potential exploration targets.

WETTABILITY

Fluid distribution and displacements in porous rocks can be considerably affected by preferential wetting of the rock surfaces. Thus the contact angle of the interface between gas and water and the surface of coal may be of considerable importance to the coalbed methane. Although some measurements of contact angles in coal have been reported (Bond *et al.* 1950; Anderson *et al.* 1986), direct measurements on coal surfaces in a reservoir engineering context do not seem to have received attention.

The measurements of contact angles in coal that have been made have been in the context of coal dust suppression and coal processing. Bond *et al.* (1950) conducted flotation experiments to determine the contact angle of the interface between gas and water with a coal surface. These experiments involve observation of small lumps of coal floating in a container of water, and the load that is required to cause them to sink. All the measurements reported are in the range 75°-95°, with an increase in coal rank corresponding to an increase in contact angle.

Anderson *et al.* (1986) measured advancing water contact angles of very fine Young-Wallsend seam and Blair Athol Coalfield coals, obtaining results in the range 67°-78°. They discuss the implications of these results to applications such as dust suppression, flotation and flocculation.

In a study of gas-water capillary pressure in coal, Dabbous *et al.* (1976) calculated equivalent pore sizes from capillary pressure data. To do this calculation, they made the assumption that water completely wets coal and the contact angle is 0° (ie. coal is hydrophilic). They recognised that the contact angle is normally somewhat greater than zero, but they refer to receding contact angles in the range from 18° to 38°.

The method we have used for determining relative permeabilities from transient displacement tests, the JBN method (Johnson *et al.* 1959), relies on being able to ignore capillary forces. Thus it is important to establish the conditions that capillary forces can be ignored in coal. As capillary forces correspond to the cosine of the contact angle, contact angles close to 90° are desirable for transient relative permeability measurements. Initial unpublished results from measurements at the University of New South Wales indicate that methane-water contact angles at reservoir pressures are indeed close to 90°.

CONCLUSIONS

Relative permeability has been measured in coal from the Bowen and Sydney Basins in our laboratory. The low permeability in many samples has created problems for relative permeability determination. The availability of larger cores will assist in overcoming this problem.

Some coals in Australia exhibit secondary mineralisation in the cleats and fracture. Calcite can be leached out with hydrochloric acid in the laboratory, leading to an increase of permeability of up to a factor of 100. Successful application of this principle in the field may render some coalbed methane reservoirs more economically attractive.

Seams rich in vitrite may be worthwhile exploration targets. This is because vitrite displays better cleat development, which is associated with better permeability.

REFERENCES

Anderson, W. G. (1987) Wettability literature survey!part 6: the effects of wettability on waterflooding. *J. Petrol. Tech.*, **39**, 1605-1622.

Arastoopour, H. and Chen, S. T. (1991) Sensitivity Analysis of Key Reservoir Parameters in Gas Reservoirs, paper SPE 21515 presented at the Gas Technology Symposium, Houston, Texas, pp.333-340.

Bond, R. L., Griffith, M. and Maggs, F. A. P. (1950) Water in coal. *Fuel* **29**, 83-93.

Buckley, S. E. and Leverett, M. C. (1942) Mechanism of fluid displacement in sands. *Trans. AIME*, **146**, 107-116.

Dabbous, M.K., Reznik, A.A., Taber, J.J. and Fulton, P.F. (1974) The permeability of coal to gas and water. *Soc. Petrol. Eng. J.*, **14**, 563-572.

Durucan, S. and Edwards, J.S. (1986) The effects of stress and fracturing on permeability of coal. *Mining Science and Technology*, **3**, 205-216.

Harpalani, S. and Zhao, X (1989) An investigation of the effect of gas desorption on coal permeability. *Proc. Coalbed Methane Symposium, Tuscaloosa, Alabama, April 17-20.*

Hyman, L. A., Ohen, H. A. Amaefule, J. O. and Daneshjou, D. (1991) Simultaneous determination of capillary pressure and relative permeability in coalbed methane reservoirs. *Proc. Coalbed Methane Symposium, Tuscaloosa, Alabama, May 13-16.*

Johnson, E.F., Bossler, D.P. and Naumann, V.O. (1959) Calculation of relative permeability from displacement experiments. *Trans. AIME*, **216**, 370-372.

Pomeroy, C.D. and Robinson, D.J. (1967) The effect of applied stresses on the permeability of a middle rank coal to water. *Int. J. Rock Mech. Min. Sci.*, **4**, 329-343.

Puri, R., Evanoff, J. C. Brugler, M. L. (1991) Measurement of coal cleat porosity and relative permeability characteristics. Paper SPE 21491, presented at the Gas Technology Symposium, Houston, Texas.

Reznik, A.A., Dabbous, M.K., Fulton, P.F. and Taber, J.J. (1974) Air-Water Relative Permeability Studies of Pittsburgh and Pocahontas Coals. *Soc. Petrol. Eng. J.*, **14**, 556-562.

Smyth, M. and Cook, A. C. (1976) Sequence in Australian coal seams. *Math. Geology* **8**, 529-547.

Stach, E., Mackowsky, M-Th., Teichmuller, M., Taylor, G.H., Chandra, D. and Teichmuller, R. (1982) Coal Petrology, Gebruder Borntraeger, Berlin, Stuttgart, 3rd ed., 535p.

Tao, T. M. and Watson, A. T. (1984) Accuracy of JBN estimates of relative permeability: part 1 - error analysis. *Soc. Petrol. Eng. J.*, **24**, 209-214.

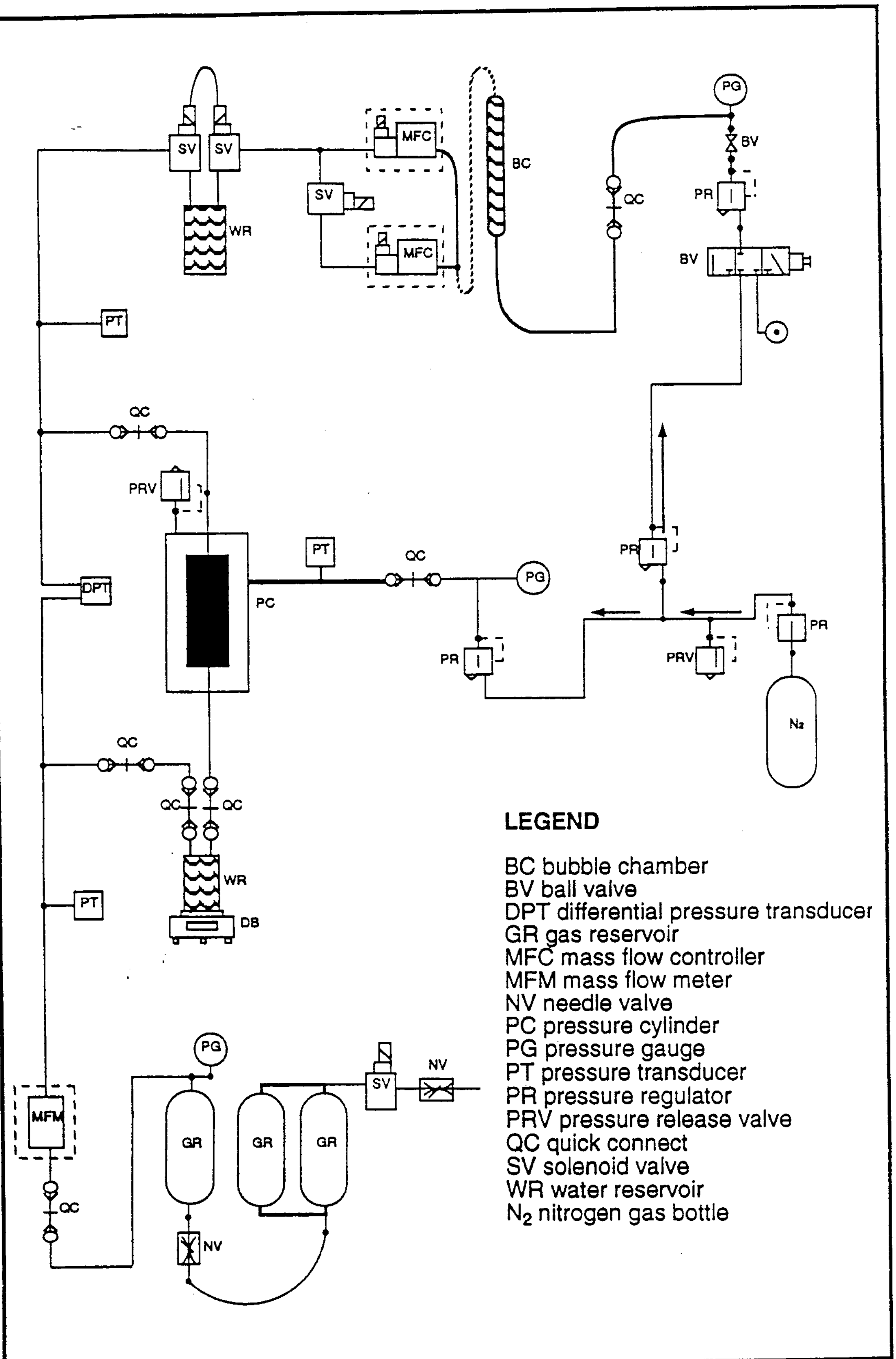

Figure 1. The laboratory apparatus for relative permeability measurement

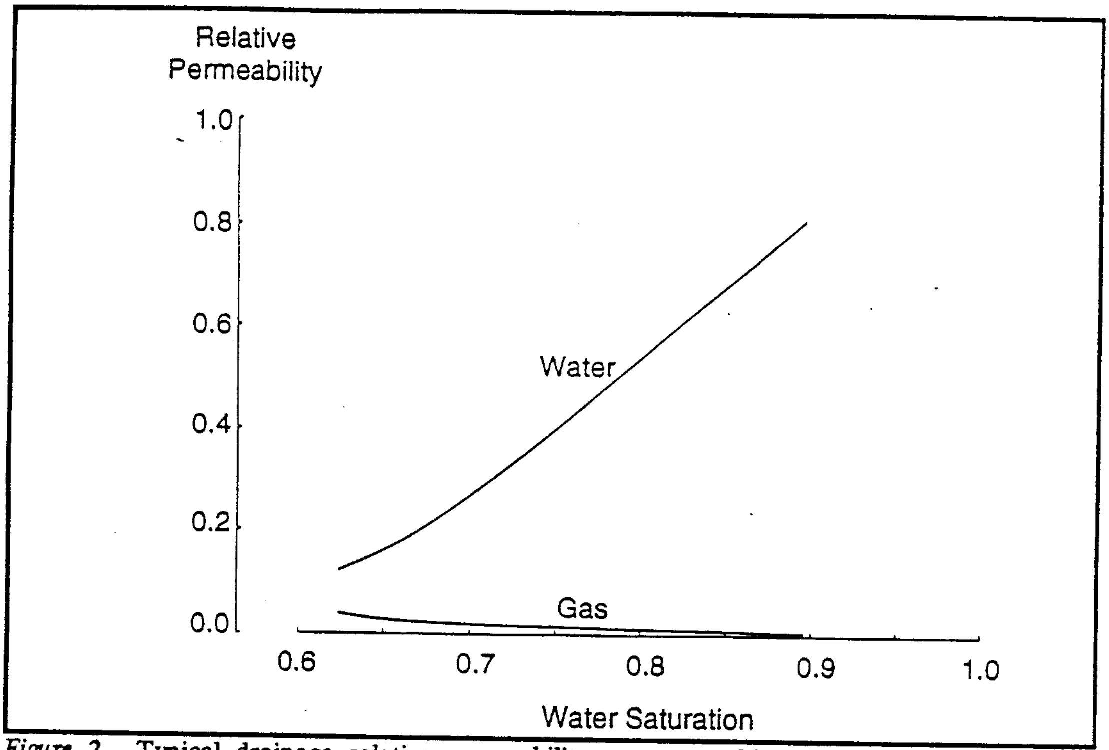

Figure 2. Typical drainage relative permeability curves resulting from measurements in a Bowen Basin coal. Low absolute permeability and sample size prevent data from being collected at lower water saturation values

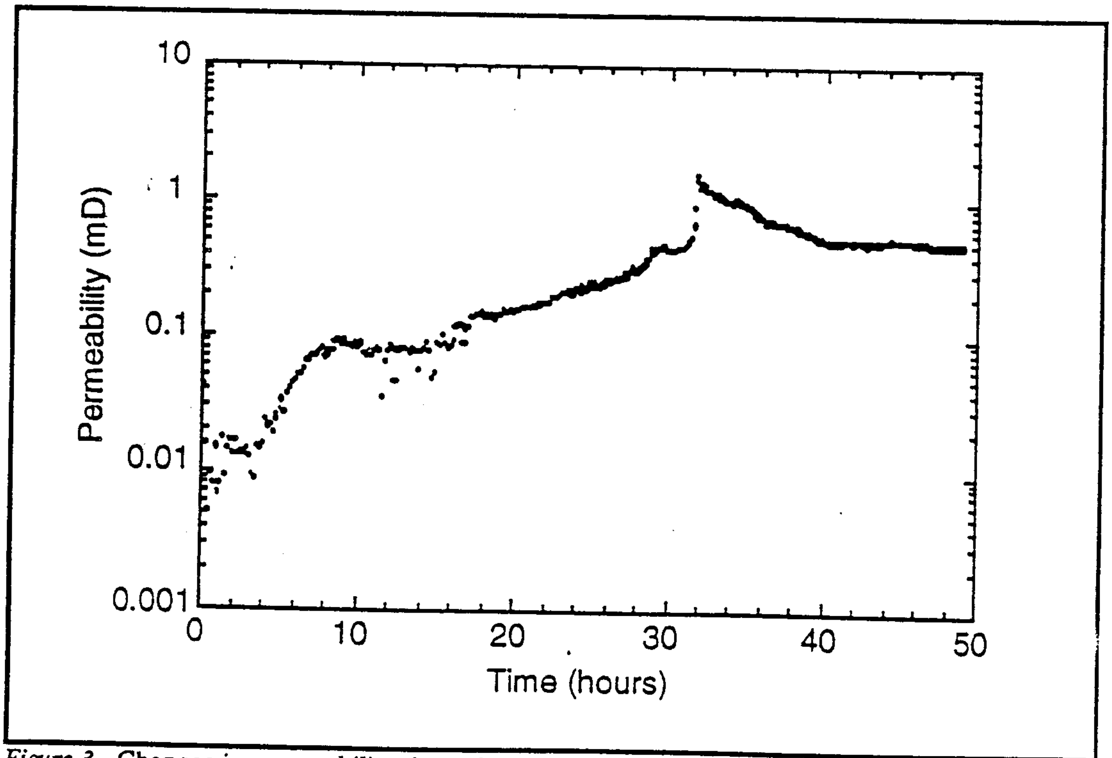

Figure 3. Changes in permeability through a coal sample while being leached with hydrochloric acid