

APPLICATION OF PREDEVELOPMENT MINING DATA TO MINE DESIGN IN REMOTE MINING AREAS

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ABSTRACT

The paper outlines the need for prefeasibility study for mine planning in a remote mining area. One of the most cost effective techniques of obtaining predevelopment design data is from exploratory borehole either by surveying rock formations intersected by small diameter open boreholes, by testing rock cores or obtaining mine hazard information by borehole testing techniques. Methods of examination of strength and deformation parameters for mine design are described. Mining hazard information which can be obtained from borehole tests and core tests are gassiness index of coal seam, hydrogeological characteristics of rock mass for the prediction of mine water inflow, spontaneous combustion risk index and the presence of abnormal in situ stress. This information can assist in the forward planning of mining operations so as to avoid unprecedented dangerous occurrences during actual mining operations.

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1. INTRODUCTION

In recent years, many multi-national mining companies have shown considerable interest in developing large coal deposits in remote mining areas or countries where no previous indigenous mining experience existed. The investment decision for such mining ventures not only depends upon financial factors and market requirements, but also on detailed technical feasibility study and risk analysis. Consideration should therefore, be given to the details for mine design incorporating stability evaluation of underground excavations and tunnels, ventilation planning and mine environmental control, design of mine dewatering or drainage control systems, and the proposed mining method. Most central design offices of multi-national companies utilize computerised mine design techniques for the detailed evaluation of mining plans. The basic quantitative data for such designs is normally obtained from the relevant tests performed on the rock cores obtained from exploratory boreholes and open hole wireline logs. This information permits quick estimations of parameters necessary for mine design. The paper outlines the range of information which can be obtained from borehole testing and the manner in which it can be assimilated in mine design. Various parameters which can be obtained from core tests and wireline borehole logs are as follows:

- Rockmass index test
- Estimated strength and deformation parameters of rock
- Gassiness index of coal seams
- In situ permeability of rockmass and core porosity
- Spontaneous combustion risk index of coal seam
- Mine drainage parameters obtained from pumping test data
- In situ stress measurement

The paper describes the authors' experience in synthesising the strength and deformation parameters of rock from the index tests performed on borehole cores. A case study also describes an application of adiabatic oxidation tests on borehole cores to evaluate spontaneous combustion potential of coal seams.

2. PREDEVELOPMENT DESIGN DATA REQUIREMENTS FOR FEASIBILITY STUDY

When the presence of a coal deposit has been discovered, a detailed drilling programme is often warranted to prove the economical viability of the deposit. This exploratory drilling programme should continue until a thorough indication of the size of occurrence, its configuration and basic characteristics have been established. The mineral exploration programme should be followed up by a feasibility study which is usually conducted in three overlapping stages:

- Quick assessment of potential profit
- Detailed economic analysis to estimate profit per tonne and potential return on investment
- Detailed engineering planning and scheduling to delineate any potential dangers

Due to recent developments in open borehole logging techniques, an outstandingly cost effective method of surveying rock formations penetrated by small diameter boreholes

is now available. The open borehole logging techniques together with the borehole core analyses and testing yield the following range of data:

1. Exploration logging information which includes:
 - Coal lithology log
 - Seam thickness log
 - **Coal quality log**
 - Density log
 - Neutron logs
 - Sonic log - which may be used for the indication coal rank, rock strength, moisture, fixed carbon content and ash content survey
2. Mine design information - which may include:
 - Geological structure information encompassing joints, fractures and bedding spacing data
 - Geomechanical characterization of rock
 - Rock strength and deformation properties
 - **In situ stress field**
3. Mining hazards information including:
 - Spontaneous combustion risk potential
 - Gas emission potential
 - Mine water inflow predictions
 - Abnormal strata temperatures and strata pressures.

The scope of this paper extends to the use of predevelopment mining data for the design of mine workings and does not necessarily relate to geophysical data relating to the exploration information.

3. PREDEVELOPMENT MINING DATA ACQUISITION

During the past decade, the NCB has embarked on an exploration and feasibility study programme for planning new coalfields, e.g. Selby, North East Leicestershire prospect, Park project etc. The development of slimline borehole geophysical instrumentation has changed the previous trend of using costly cored boreholes for coal exploration. In order to reduce the cost of core drilling from the surface, one of the following procedures may be adopted for the acquisition of mine design data:

- Open borehole drilling from the surface to the top of the Coal Measures, followed by detailed core drilling in the proximity of the coal seams. These boreholes can be logged by using slimline geophysical boreholes tools to generate a variety of borehole data. Cores obtained from the borehole and further tests performed in the borehole cavity may give further data for mine design.
- Complete wireline drilling for detailed geophysical logging using a variety of slimline instrumentations. The open boreholes can be further used for obtaining hydrogeological and other relevant data for mine design and hazard analyses.

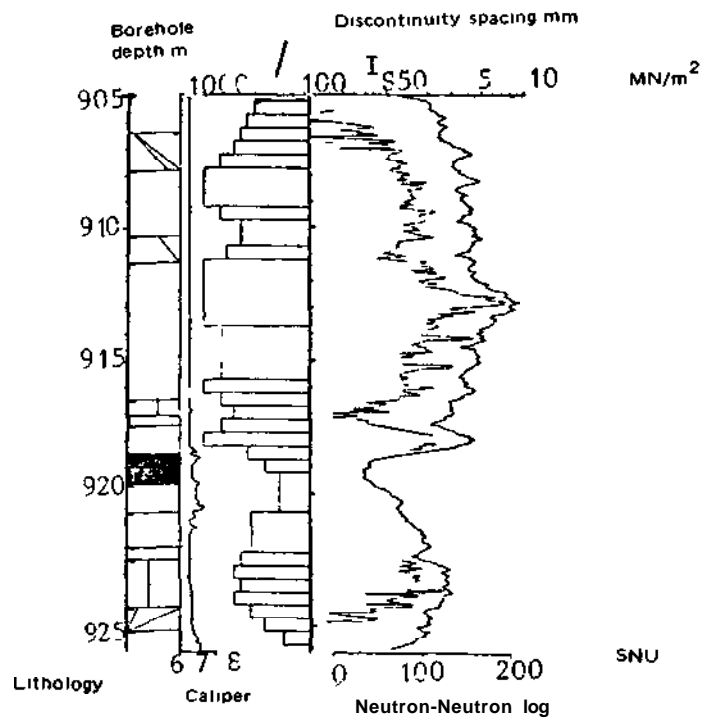


Figure 1— Borehole log response and index properties [Singh et al 1983]

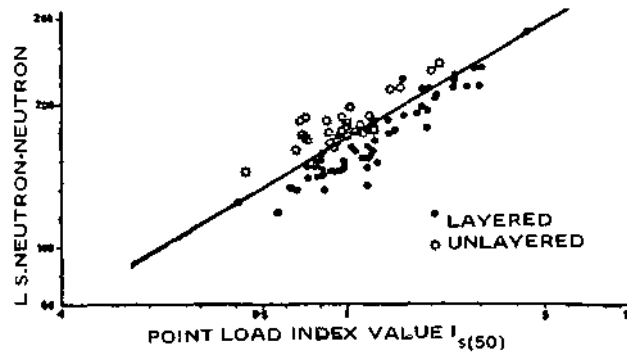


Figure 2— Relationship between L S Neutron-Neutron log and $I_s(50)$ index test [Singh et al 1983]

During the past six years considerable research efforts have been made for the establishment of a geophysical data base from several open borehole prospecting sites and to relate these to geotechnical data including the point-load index and Rock Quality Designation (RQD). Elkington et al (1982), Stouthammer (1980), Elkington (1981). Figure 1 shows a section of raw point load data, discontinuity spacing data together with the neutron log and caliper log response. Figure 2 is a plot of point load index versus neutron log response for the complete borehole.

4. ESTIMATION OF STRENGTH AND DEFORMATION PARAMETERS FOR MINE DESIGN

An approach to obtain strength and deformation parameters of rock for mine design is the determination of rock mass index from borehole core tests or from borehole geophysical logs and estimate the required design parameters by correlation.

4.1. Types of Index Test

Types of index tests suitable for borehole cores from friable Coal Measures rock are summarized in Table 1. Index testing techniques have been designed to overcome some of the difficulties encountered in the laboratory test as follows:

- Minimum sample preparation at the borehole site
- Test is performed on portable equipment
- Quick and inexpensive tests

Table 1 also indicates the test requirements, sample size and shapes, loading geometry, loading rates and limitations of each test type. An earlier publication presented point load index; Schmidt hammer rebound test and slake durability tests results and their empirical correlations with the strength and deformation parameters of coal measures rocks (Singh et al 1983). Table 2 summarises the relationships between index tests and various strength and deformation parameters of rock mass.

In this paper an attempt has been made to correlate the results from the N.C.B. cone indenter hardness and shore scleroscope tests with the strength and deformation parameters of rocks. The data for this analysis has been derived from 4 different projects including Neyveli Lignite project, Rossing Uranium project S.W.A., Sweden and the Undersea trenching operations at Folkstone. Table 3 presents the summary of rock test results from the above projects.

5. MINING HAZARD INFORMATION

The purpose of mine hazard analysis is to define the in situ conditions influencing the minability of a coal prospect from scant borehole information so as to avoid unpredicted occurrences when the mining operations have actually commenced. For example, a sudden inflow of water (yielding up to 80×10^6 β) at Wistow mine (at A1 face) only a few weeks after it opened; caused one of the biggest shocks and disappointments in the British coal mining industry (Annon 1984). One of the techniques to highlight potential mining hazards is to construct composite mine hazard plan showing anticipated problem areas [Thurman et al 1978]. The mine design can then be adapted for the deposit to minimize the danger of encountering unacceptable working conditions. Such a mine plan should be based on the worst conditions likely to occur and should be modified as more information from the mine is accumulated.

Types of information which is required prior to the detailed mine planning is as follows:

- Gassiness of coal seam
- Hydrogeological information for the prediction of ground water inflow

Table 1— Index testing techniques for intact rock

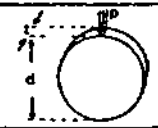

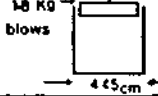
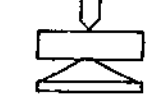


Test Type	Loading Geometry	Parameters	Sample			Loading Rate	Recommended Loading Geometry	Limitations
			Diameter	h/d Ratio	No samples			
1. Brinell		$qc = \frac{2P}{\pi d^2}$	HX core 56 mm	0.5:1	3	0.64 cm/min	1. Loading through curved jig jaw with spherical seating ii. Angle of contact = $\frac{1}{6}$	Failure in bias of stress field
2. Point Load I_{ps}		$I_{ps} = \frac{P}{d^2}$ $qc = 24I_{ps}$	50 mm	1-1.5	10-15	No standard loading rate		
3. Impact strength (Evans)		$qc_2 = 76912 - 36360$	+ 32 mm		6	Impact rate should not be faster than 1 per 2 sec		Results should be used to estimate resistance to degradation and workability of rock
4. Comp. Strength by cone indenter		D = deflection of strip I = depth of indentation $qc = \frac{D}{I^2}$	1. 12.5 mm x 12.5 mm x 6 mm or 2. 27 mm dia. and 12 mm thick	0.1:1	6		A min. depth of indentation should be 0.2-0.25 mm	1. Specimen should not be tested near the edge of specimen 2. Core is 15 mm dia. to rock with $qc < 150 \text{ MPa}$
5. Schmidt Hammer		advisable to use 740 mm diameter					core size 400 mm can be applied to unshaped joint surface	Not advisable to use small dia. core after
6. Slake durability		$SD(d) = \frac{\text{Final dry weight}}{\text{Initial dry weight}}$	60-60 mm		10 lumps		Can be applied to unshaped lumps	Errors large for small no. test of slake durability
Shore Scleroscope	Model C-2	Shore hardness scale 0-140	12.50 mm	Min. thick = 1 cm surface = 1 cm ²	20 determinations	Indentation spacing 5 mm	Slitting surface discula = 0.1 to 0.4 D	Flat surface containing 400-600 abrasive powder

Table 2— Estimation of strength and deformation parameters from various index tests

Type of Index test	Point load index 'I _S '	Schmidt hammer test
1. Parameters	$I_S = \frac{P}{d^2}$ d = specimen diameter (m)	I _{SH} = POINT INDEX NUMBER
2. Derived index	$I_{S50} = 0.256 + \log_{10} I_S - 1.008 e^{-0.027d}$	---
3. Estimated uniaxial comp. strength σ_c	29 I _{S50}	$\sigma_c = 2 I_{SH}$
4. Tensile strength σ_t	2.76 I _{S50}	$\sigma_t = 0.23 I_{SH} - 0.81$
5. Cohesive strength	$c = \frac{29}{2} I_{S50} \times \frac{(1 - \sin \phi)}{\cos \phi}$	$c = 8.17 + 0.305 I_{SH}$
6. Triaxial stress factor	---	$K = 2.98 + 0.031 I_{SH}$
Tan ϕ	---	$\left(\frac{1.98 + 0.031 I_{SH}}{2\sqrt{2.980 + 0.031 I_{SH}}} \right)$
σ_1	$29 I_{S50} \left[\frac{\sigma_n}{\sigma_c} + \frac{T_{max}}{\sigma_c} \right]$	$2 I_{SH} + (2.98 + 0.031 I_{SH}) \sigma_3$
τ	---	$(8.17 + 0.305 I_{SH}) + \sigma_n \tan \phi$
E	---	$(25.37 + 0.52 I_{SH})$ GPa
$\frac{1 + \nu}{E}$	---	$(159.3 - 3.36 I_{SH}) \times 10^{-12}$

- In situ stress measurement
- Spontaneous combustion risk index

5.1. Gassiness of Coal Seam

The possibility of an explosion resulting from the emission of methane into mine workings is a major hazard in underground coal mining. In order to design safe mine

Table 3— Summary of rock test results

Rock Type	Mean Protodyakanov Number	Uniaxial Compressive Strength σ_c MPa	Uniaxial Tensile σ_t MPa	Young's Modulus E GPa	Poisson's Ratio ν	Cerchar Abrasivity Index	Toughness Index T_1	Shore shterscope	NCB Cone Indentor
Green sandstone	7.66	83.05	8.30	10.06	0.095	4.25	34.30	70.40	4.43
Haemetitic sandstone	10.35	115.67	7.56	41.69	0.120	3.32	16.05	77.22	4.84
Sandstone	2.43	73.89	6.21	55.29	—	4.16	5.77	64.80	4.10
Sandstone	6.41	67.84	6.32	58.95	—	2.48	3.90	32.17	2.02
Porous sandstone	6.03	30.91	6.14	9.47	0.035	4.25	5.04	28.33	1.82
Sandstone	3.89	25.51	5.60	5.78	0.099	4.03	5.47	54.52	3.43
Granite		166.50	8.06	62.33	0.138	3.46		91.77	12.49
Granite		174.70	7.52	41.43	0.145	3.60		94.40	7.98
Larvekite		192.27	8.78	63.03	0.246	3.58		92.00	13.84
Red granite		158.88	6.87	51.71	0.276	2.84		98.90	16.04
Diorite		194.77	11.89	55.20	0.390	3.75		81.08	9.89
Olivine gabbro		211.80	12.51	67.25	0.167	3.32		82.00	14.04
Granite		190.06	10.89	57.98	0.248	3.98		97.10	12.43
Portland sandstone		83.65	4.52	20.74	0.147	2.12		42.50	2.77
Cuddalore sandstone		1.58				1.36		9.34	1.56
Pyroxene gneiss						4.65		81.70	10.34
Pyroxene garnet gneiss						3.46		95.70	11.96
Amphibolite						4.48		63.16	9.71
Pyroxene garnet gneiss						4.01		84.75	6.23
B.A. Schist						3.60		43.90	4.18
Marble						4.17		46.97	3.78
B.C. Gneiss						4.56		72.90	5.69
Pegmatite granite						4.69		94.26	9.50

working conditions from this hazard, some indication of the rate of emission of gas should be known so that adequate quantities of air are supplied to the mine workings. If necessary, a provision for methane drainage could be made. The first indication of in situ gas content of the coal seam can be obtained from borehole tests which involve collecting borehole core samples for measurements in the laboratory. An alternative approach is to calculate methane content from the measurements of in situ gas pressures with a knowledge of the relevant adsorption isotherm of coal.

The direct method comprises of samples of cores taken from surface boreholes and to evaluate their methane content under controlled laboratory conditions. Surface borehole cores are sealed in special containers with sampling valves to permit measurement of the rate of gas emissions and therefore, the gas lost before grinding. The coal is pulverized in a pressurized grinder to prevent gas escaping from the grinding mill and to prevent oxidation of the coal. Two hours after crushing in the mill the gas compositions, temperature and pressure are measured. The resulting gas content is corrected for the gas which remain absorbed to the crushed coal by using an average adsorption isotherm to give total methane content.

There are several variations of direct method of the determination of gassiness of coal seams, these are as follows:

— The MRDE method comprises obtaining surface borehole cores and transporting them in sealed vessels with sampling valves to facilitate measurement of rate of gas emission and hence the gas lost before milling operation. The grinding mill is evacuated and pressurized with nitrogen at 1.4 atmosphere absolute to ensure gas flow the mill to the analyser and also prevent oxidation of coal.

— When the coal sample is taken from a vertical borehole with a mud drilling medium the pressure load of the mud prevents desorption until the sample is partially removed from the hole.

— Loss of gas during drilling can also be minimised by using a core barrel which can be hermetically sealed around the coal sample in situ. A further technique of reducing desorption is by freezing the sample in situ.

The indirect method consists of drilling a vertical borehole to a coal seam, sealing a section of the borehole, measuring the equilibrium gas pressure of the seam and a laboratory determination of the quantity of gas held by the particular coal at a given pressure. The latter is determined by using the relevant adsorption isotherm shown in Figure 3.

The various drawbacks of this method are as follows

- Inaccuracies due to the effects of water in the coal strata
- Corrections for the effects of ash content and volatile content of coal
- Method is costly

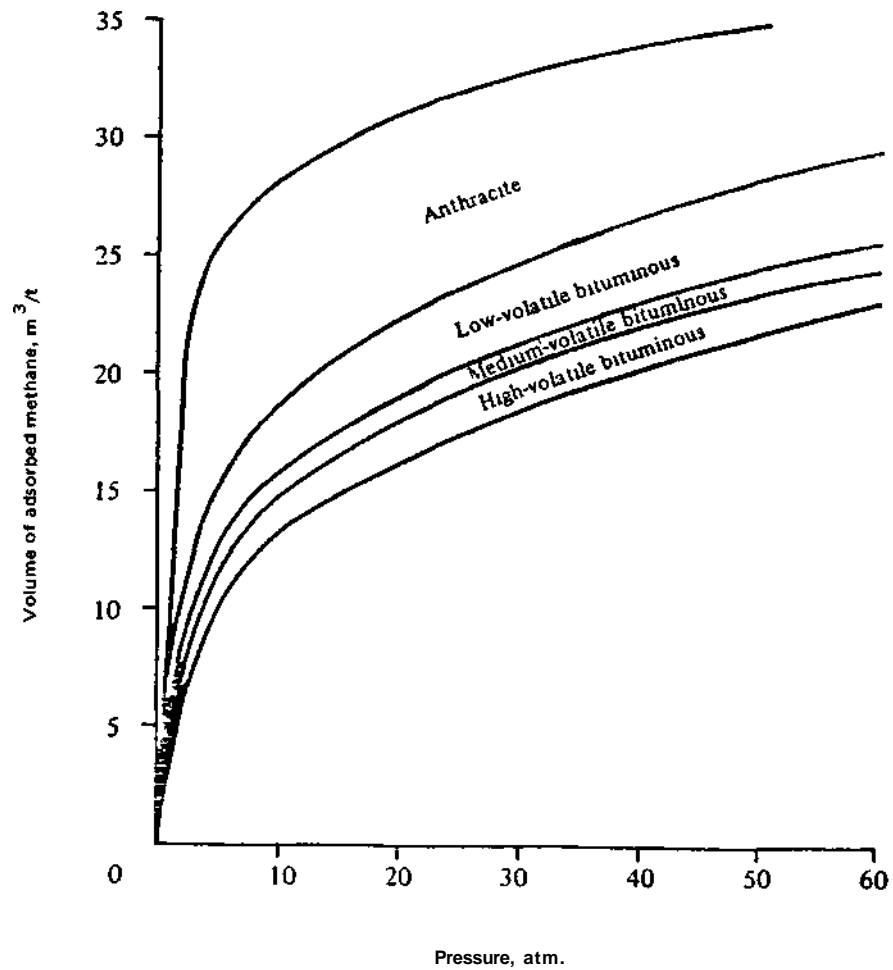


Figure 3— Variation of methane adsorption isotherm with coal rank at 0°C (40) (after S. Curl)

5.2. Hydrogeological Information for the Prediction of Ground Water Inflow

Exploratory boreholes can be used for conducting hydrogeological tests for the evaluation of hydrogeological characteristics of rock mass as follows:

- Aquifer thickness and geometry
- Transmissivity and permeability
- Storage coefficient
- Piezometric surface of each aquifer

Two types of tests are convenient during the feasibility stage, packer tests and pressure recovery tests.

The packer test is applicable to minor aquifers such as Coal Measures rock and comprises isolating a section of borehole by expandable packers to form a test cavity for performing a constant pressure pumping in test. The constant rate of pumping can be related to the borehole geometry, the test pressure and the coefficient of permeability as follows:

$$K_H = \frac{q \log_e (2m L / d)}{2 \pi L H_c}$$

where

K_v : vertical permeability

κ_H : horizontal permeability

$$m = \left(\frac{K_v}{K_H} \right)^{\frac{1}{2}}$$

q : flow rates, m^3/s

H_c : constant head of water

L : length of test cavity, m

d : borehole diameter, m

The pressure recovery test is applicable to major confined aquifers and entails the pumping out of water from a borehole intersecting a confined aquifer for a given time and loss in pressure is recorded. See Figure 4. The pumping is stopped and time for the recovery of the aquifer pressure is observed. The rock mass permeability can be calculated by using Theis recovery formula:

$$T = 0.183 \frac{q}{D} \log \frac{t + \Delta t}{\Delta t}$$

where

T : transmissivity

q : well discharge prior to shut off, m^3/d

t : pumping out time

Δt : time for recovery of piezometric surface since pumping has stopped

D : change in piezometric head, m

With the knowledge of aquifer characteristics it is possible to estimate the quantities of mine water inflow. [See Singh et al 1984a, 1984b].

5.3. Estimation of in Situ Stress Field

One of the most important parameters taken into consideration during mine design is the presence of high in situ strata stresses. It is therefore, desirable to determine virgin

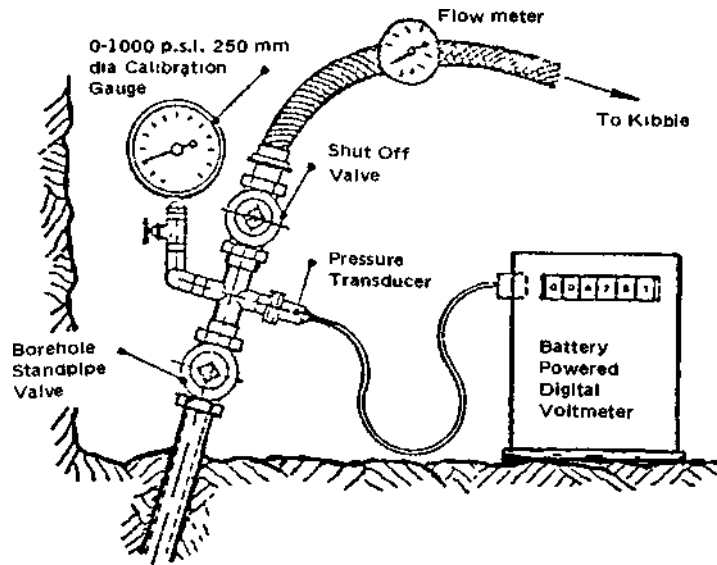


Figure 4— Pressure Recovery Test

rock stress during the later stage of mine exploration. Two well established techniques of stress measurement which can be applied to deep exploratory boreholes drilled from the surface are hydraulic fracturing and stress relaxation techniques. A detailed description of each method will be out of place.

Briefly, hydrofracturing technique consists of isolating a small section of a borehole at a desired depth by two inflatable packers and applying an hydraulic pressure on the borehole wall. The borehole should be oriented in the direction of one of the principal stress components. During the test, initial water pressure, maximum pressure before rock failure, fracture pressure and shut-in pressures are measured. The direction of fracture initiation, whether a vertical fracture or fracture initiated vertically but extending horizontally, will determine the method of analysis. These values enable two horizontal components of principal stresses to be evaluated. The vertical stress can be estimated as a stress caused by the overburden pressure. [See Enever 1975].

Strain relaxation technique originally suggested by Voight (1969) consists of recovering a borehole core from the site of stress measurement and precisely measuring the total recoverable time-dependent strains on the core with time. Strain relaxation measurements are made by using strain gauge rosette technique incorporating miniature strain gauges installed on the surface of the core at predetermined directions. This enables the measurement of the relevant strain relaxation ellipsoid which in turn permits the directions and relative magnitudes of the initial principal stresses on the borehole core to be calculated.

The above techniques, will in many instances provide relatively reliable information regarding the directions of principal stresses. These information aids in the initial design of a mine layout particularly deciding on the orientation of major underground excavations.

5.4. Spontaneous Combustion Risk Index

Many mining consultants reviewing major coal development projects in remote mining areas assess the liability of coal seams to spontaneous combustion by testing cores obtained from exploratory boreholes. Usually, cores are obtained both from coal seams and its immediate surroundings. Cores are flushed with nitrogen immediately after their recovery from the core-barrel and successively sealed with clingfilm, metallic foil, hessian cloth and wax. The susceptibility of coal to spontaneous combustion is determined by conducting adiabatic oxidation tests in the laboratory. The tests are conducted under following conditions:

- (i) in situ moisture coal/saturated air
- (ii) vacuum dry coal /saturated air
- (iii) vacuum dry coal/dry air

Experience has shown that the second test condition promotes spontaneous heating. The criterion for proneness to spontaneous combustion is based on initial rate of heating, total temperature rise and together with a combination of extrinsic factors, discussed elsewhere [see Singh, Demirbielik and Turney 1984]. Figure 5 shows the intrinsic reactivity curves for coal obtained from boreholes from the exploration sites. It can be seen that for all these coal samples the initial rate of heating was between 1.4 to 1.6°C/h. All the three coals were classified as high risk coals. Subsequent experiences showed that all the three coals presented spontaneous combustion problems. The results also indicate that the intrinsic reactivity test on borehole cores is a valid technique of spontaneous combustion risk classification.

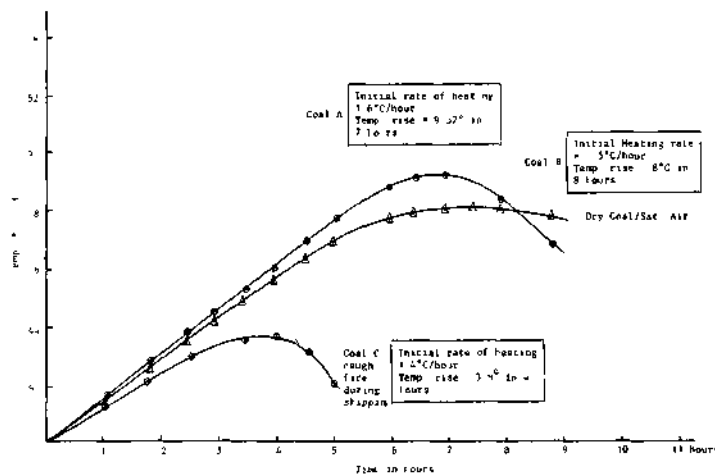


Figure 5— Intrinsic Reactivity curves for coals obtained from boreholes from exploration sites

6. CONCLUSIONS

The development of a new underground mining project takes several years from its conception to the completion stage and requires large capital investments. It is therefore, imperative that the mine should be planned in sufficient detail during the feasibility stage in order to assess the major mining hazards and potential profits. Any unforeseen occurrences during the exploitation stage of the project may jeopardize the entire project. Predevelopment design data for a feasibility study should be obtained during the exploration stage. The type of information which can be obtained from exploratory boreholes are as follows:

- Exploration logging information
- Mine design information
- Mining hazard information regarding the danger of inundation, large influx of gas, regional instability, danger of fires due to spontaneous heating and outburst etc.

The design data obtained from the boreholes during the exploration stage must be treated with caution and updated as the mine develops.

7. ACKNOWLEDGEMENTS

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REFERENCES

1. ANON (1984) 'Wistow-What Went Wrong?' World Mining Equipment, p. 32-35, Jan.
2. ENEVER, J.R. (1975) 'The Measurement of Rock Stress at Depths From Small Diameter Surface Drill Holes'. The Australians I.M.M. Conference, South Australia, June, pp. 551-560
3. ELKINGTON, P.A.S. (1981) Wireline Loggings and Coal Measures Rock Strength, Ph.D. Thesis, Mining Dept., Nottingham University, p. 156
4. ELKINGTON, P.A.S., STOUTHAMER, P. and BROWN, J.R. (1982) Rock Strength Predictions From Wireline Logs, Int. J. Rock Mech. Min. Sei., Vol. 19, pp 91-97
5. SINGH, R.N., ATKINS, A.S. and AZIZ, N.I. (1984a) "Basic Analytical Techniques for the Prediction of Mine Water Inflow", International Journal of Mining Engineering, June
6. SINGH, R.N. and ATKINS, A.S. (1984b) 'Advanced Analytical Techniques for the Prediction of Mine Water Inflow', International Journal of Mining Engineering, June
7. SINGH, R.N., DEMIRBILEK, S. and TURNEY, M. (1984c) "Application of Spontaneous Combustion Risk Index to Mine Planning, Safe Storage and Transport of Coal", 4th National Coal Congress, Zonguldak, Turkey, May 7-12
8. SINGH, R.N., HASSANI, F.P. and ELKINGTON, P.A.S. (1983) "Application of Index Testing Techniques to the Stability Evaluation of Coal Measures Excavations", 24th Rock Mechanics Symposium, Aston, Texas, U.S.A. p. 599-610
9. STOUTHAMER, P. (1980) 'Evaluation of Coal Prospects', M. Phil Thesis, University of Nottingham
10. THURMAN, A.G., STRASKRABA, V. and ELLISON, R.D. (1978) 'Development of a Ground Water Hazard Map for an Underground Coal Mine', Water in Mining and Mining Works, Granada, Vol. 1, p. 273-292, Sept.
11. VOIGHT, B. (1968) Determination of the Virgin State of Stress In the Vicinity of a Borehole From the Measurements of a Partial Elastic Strain Tensor in Drill Cores, Felsmachanlk a Ingenieurgeol, 6