CATEGORISATION OF ROCK STRATA IN AUSTRALIAN COAL MINES WITH RESPECT TO POTENTIAL FOR METHANE IGNITION BY FRICTIONAL EFFECTS

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EXECUTIVE SUMMARY

A sophisticated suite of laboratory instrumentation has been constructed to investigate on a quantitative basis the forces and temperatures associated with ignition of methane-bearing mine atmospheres by rock friction. The instrumentation has been calibrated and tested on rocks from both Australian and overseas coal mines, and found to give satisfactory, reproducible results.

The instrumentation uses a cone-sensing shell dynamometer, specifically designed by the research team for rock-on-rock frictional testing. This is complemented by an infra-red sensing pyrometer, which monitors temperatures developed at the frictional hot-spot in indiividual laboratory tests. Electronic real-time output of signals from both the dynamometer and the pyrometer, representing the dynamic normal, frictional and transverse forces as well as the temperature, is processed by a high-capacity computer system to provide graphical and numerical records of individual ignition tests. These can be synchronised with records from a video camera, also processed by the computer system, to evaluate all relevant aspects of the laboratory ignition process.

Investigation of an extended suite of rock samples, including several rock types not previously subjected to ignition testing, has confirmed the correlations between rock composition parameters and frictional incendivity categorisation (IGCAT) developed by Ward et al. (1990, 1991a,b). Some revisions have been made to the relevant equations and diagrams as a result of the present study, and updated information is included in this report.

Attention is drawn in particular to the ignition risk associated with silicified bands in coal seams, at least some of which occur in conjunction with intra-seam tuffaceous claystone horizons. Such materials have been identified by the study as the most likely cause of a 1994 ignition in a New South Wales mine. It is recommended that methods for identifying these materials at the face or in drill holes, and of predicting their occurrence at mine sites, be further investigated.

Rock-on-rock tests using the instrumentation developed for the project show average dynamic friction coefficients of between 0.48 and 0.75. Maxima are considerably higher, however, due to transient effects such as surface irregularities and wheel jams.

Temperatures of between 1100 and 1550°C have been measured at the frictional hot-spot in rock-on-rock studies. These temperatures are developed quickly (< 1 second) in the course of individual ignition tests. They are typically well above the value normally required to ignite a methane-air mixture in laboratory conditions.

Analysis of video records from individual ignition tests show that methane ignition mostly originates slightly behind the hot-spot developed from rock-on-rock friction in the test rig. This is consistent with the hot-spot itself acting as the ignition source, rather than incandescent particles (sparks) generated by the frictional heating process. The point of origin behind, rather than at the hot-spot is explained by a time delay in development of the ignition reaction.

Although only limited data have been obtained at this time, broad positive correlations are tentatively suggested between the rock ignition category (IGCAT value) and mean friction coefficient and mean hot-spot temperature. These correlations need to be further tested before meaningful conclusions can be drawn. Correlations between friction coefficient or hot-spot temperature and rock composition parameters also require further testing in the instrumented ignition rig.

It has been found in the course of the study that brittle rocks such as siliceous coal, or materials for which large samples are not readily available, can be facilitated by friction against a wheel of an unmatched rock type with known IGCAT characteristics. This procedure has been subjected to preliminary investigations, and has great potential to simplify the ignition testing process. Further work on the procedure, and on other aspects arising from the work, will be continued during 1996 at the University of New South Wales.

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  - Igor Pluzhnik (Research Assistant)
  - David Coates (Technical Assistant)
  - Ali Bashari (Technical Assistant)
  - Tim Positti (Technical Assistant)

- University Staff
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1 INTRODUCTION

1.1 Background

Due to the decline in frequency of ignitions from other sources, processes associated with rock friction are now regarded as the most common cause of methane gas ignition in modern underground coal mines. Frictional ignitions in coal mines may arise from metal-on-rock interactions, including the impact of shearer or continuous miner components on hard non-coal strata. Several incidents, however, have been reported which suggest the possibility of gas ignition from rock-on-rock friction associated with roof falls. As gas does not only accumulate in coal mines, potential also exists for frictional ignitions of methane to take place in some civil engineering projects, such as tunnels in the Sydney region, and other types of industrial installations.

The need for research on gas ignition by rock friction in the Australian coal industry was highlighted by the Warden's Inquiry into the 1986 explosion at Moura No 4 Underground Mine (Lynn et al., 1987), which recommended in part that:

> *"The necessary funds be made available to enable continued research and experimentation into the phenomenon of frictional ignition. The purpose of this research should be to ultimately establish a standard whereby all strata rocks found in Queensland can be classified according to their degree of incendivity."*

As an initial response to this recommendation, research on frictional ignition from Australian coal mine rocks was carried out between 1987 and 1990 at the University of New South Wales, with NERDDP support (Ward et al., 1990, 1991a,b). This project made use of a specially-constructed test rig in which a rock specimen was pressed, with a measured force, against a 150 mm diameter wheel of the same material rotating at a controlled speed in a methane-air atmosphere within an enclosed gas chamber. The work provided an experimental basis for grading the rocks from Australian coal mine areas on a five-point scale with respect to their rock-on-rock frictional incendivity. It also provided a database for statistical correlation of this incendivity index with the mineralogy, chemical composition and geomechanical properties of the rocks concerned, and hence became the key to understanding more clearly the role of the various rock constituents in rock-on-rock frictional ignition processes. The study identified a more relevant framework for predicting the incendivity potential of rocks in Australian collieries than previously available from overseas classifications.

Parallel work on rock-on-rock frictional ignition was conducted, with NERDDP support, between 1988 and 1991 by the Safety in Mines Testing and Research Station (SIMTARS) of the Queensland Department of Resource Industries (Golledge et al., 1991). This work demonstrated the possibility of gas ignition by rock friction from single-impact grazing collisions at speeds attainable in colliery roof falls, and further highlighted the potential for ignitions to arise in association with roof falls. It was not, however, able to establish any particular relationships between ignition potential and other rock properties.

Most other research on frictional ignition in recent years has been concentrated on the improvement of mining equipment design, rather than on rock characterisation. Such studies normally involve testing of particular cutting operations on only one, or at most a very small number of different types of rock material. Such studies are very useful in identifying the processes associated with ignition by pick-on-rock interactions, and offer scope for develop methods to reduce much of the ignition risk in mining operations. They are, however, complementary to the objectives of the present study, namely to develop better methods of characterising the intrinsic frictional incendivity of the different rocks that may be encountered in underground coal mines.

1.2 Objectives

The objectives of the present study, as indicated in the original application for support, were:

1) To develop further the procedures for testing the relative susceptibility of different coal mine rocks to frictional ignition of methane gas in underground coal mines;

2) To investigate the mathematical relationships and experimental factors that govern frictional ignition phenomena for different rock types with respect to rock-on-rock and metal-on-rock processes;

3) To establish and validate a "standard" test procedure, acceptable to the coal industry, to assess frictional potential of different rock samples;

4) To establish appropriate guidelines, from such test results, to identify high and low-risk strata in mining situations.

1.3 Project Personnel

Work commenced on the project after finalisation of contractual matters in March, 1993. The field and laboratory work program on which the present report is based was completed in December, 1995.

The following people were involved with the design and implementation of the project.

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2 PREVIOUS AND OTHER RELATED WORK

2.1 Literature Review

A summary of investigations into frictional ignition phenomena up to the late 1980s is provided in the report on the previous project at the University of New South Wales, funded under the National Energy Research Development and Demonstration Program (NERDDP) between 1987 and 1990 (Ward et al., 1990). This includes a discussion of the physics of kinetic and static friction, as well as the behaviour of rocks and minerals under frictional heating. It also includes a review of previous frictional ignition experiments related to coal mine situations, with special reference to studies attempting to categorise rock materials in terms of frictional incendivity. The latter include the work of Burgess and Wheeler (1928), Wynn (1952), Nagy and Kawenski (1960), Datey (1963), Rae (1961, 1964a,b), Ramsey et al. (1965) Blickensderfer et al. (1974) and Powell and Billinge (1975). The work summarised by Powell and Billinge (1975) was also used to develop a mineralogically-based categorisation of frictional ignition potential (National Coal Board, 1984) used by default in many countries to identify rocks associated with ignition risks. This was refined by the Australian-based work of Ward et al. (1990, 1991) prior to commencement of the present investigation.

2.2 Relative Incendivity of Rock Materials

Ward et al. (1990, 1991a,b) carried out a comprehensive investigation of the geological factors associated with frictional ignition, concentrating on the relative incendivity of rock materials found in Australian underground coal mines. A five-point incendivity categorisation scale was developed (Figure 2.1), based on the relative ease of igniting a 7% methane/air mixture by rock-on-rock friction at three different contact speeds in a rotating-wheel test rig. The categorisation (IGCAT value) was found by statistical correlation to be related to the relative proportions of hard framework particles (quartz, rock fragments, feldspar), clay matrix and carbonate minerals as determined by petrographic analysis, or to the relative proportions of quartz (by X-ray diffraction), carbonate (by acid solution) and volatile constituents (loss on ignition) as determined by geochemical and mineralogical analysis (Figure 2.2).

Complementary work by Golledge et al. (1991), also funded under the NERDDP, showed that ignition of methane-bearing natural gas could be achieved by single grazing impacts, individually of less than 20 ms duration, between two rock samples (100 mm cubes) from Australian coal mines, at relative velocities of 7 to 8 m/s. The contact speeds correspond to velocities expected from drops of 2.5 to 3.5 m in a colliery roof fall. Although the energy released in the individual contacts was also monitored, no correlation between rock properties and relative incendivity was found in this experimental study.

2.3 Relative Incendivity of Ceramic Materials

A more recent series of experiments was conducted by Tolson and Brearley (1995) to assess the relative incendivity of a range of ceramic materials, including partially-stabilised zirconia (PSZ). This work provides a useful complement to existing studies of natural rock materials. PSZ and ceramic (99% alumina) sliders were rubbed against disks of PSZ, MZF (zirconia toughened alumina) and various other materials, including alumina (99%, 97% and 94%), alumina-coated steel and CrO_2 coated steel, in air with either 15% hydrogen (most experiments) or 7% methane present.

Although not necessarily of direct significance at present to mining, the results of this study showed a considerable degree of variation in relative incendivity of the different materials, measured by the minimum power (normal force x coefficient of friction x rubbing speed) to cause ignition to occur. A minimum power of 800 to 1600 watts was required for ignition of a hydrogen atmosphere for most of the materials at rubbing speeds of 1.9 m/s (Figure 2.3). Lesser amounts of power, in some cases a little over 200 watts, were required to achieve ignition at lower speeds. Only a limited amount of testing was carried out in a methane atmosphere. but the material tested in 7% methane (PSZ block against a PSZ disk) required only a slightly higher level of power to cause ignition than that required for comparable materials to ignite the 15% hydrogen mixture used (Table 2.1).

It should be noted that the power values derived for these experiments were only measured indirectly, using the applied (static) loads and an assumed value of 0.5 for the friction coefficient.

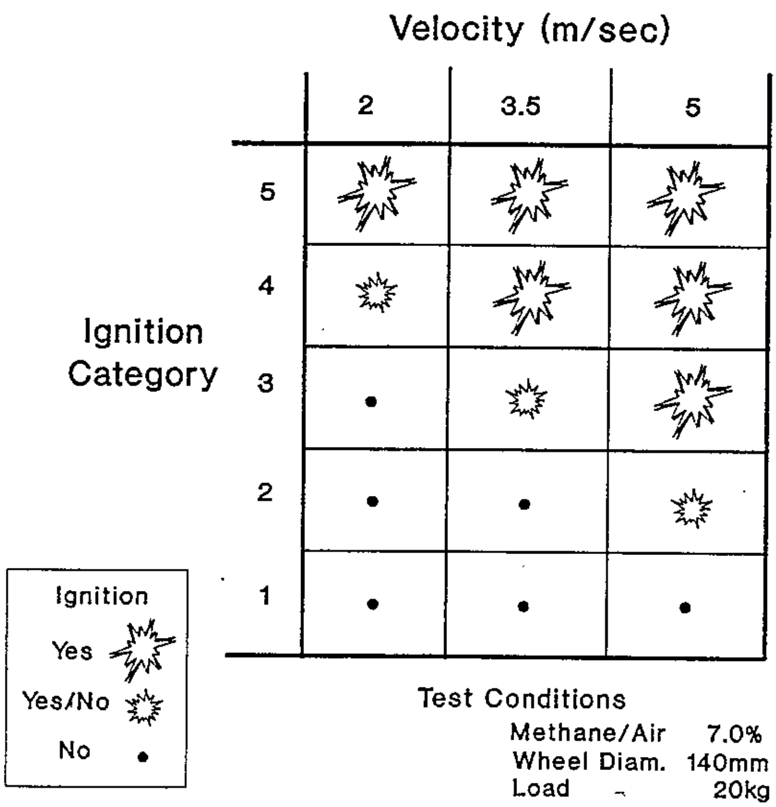


Figure 2.1: Igntion catgorisation (IGCAT) system, based on rock-on-rock ignition at different speeds, developed by Ward et al. (1990, 1991).

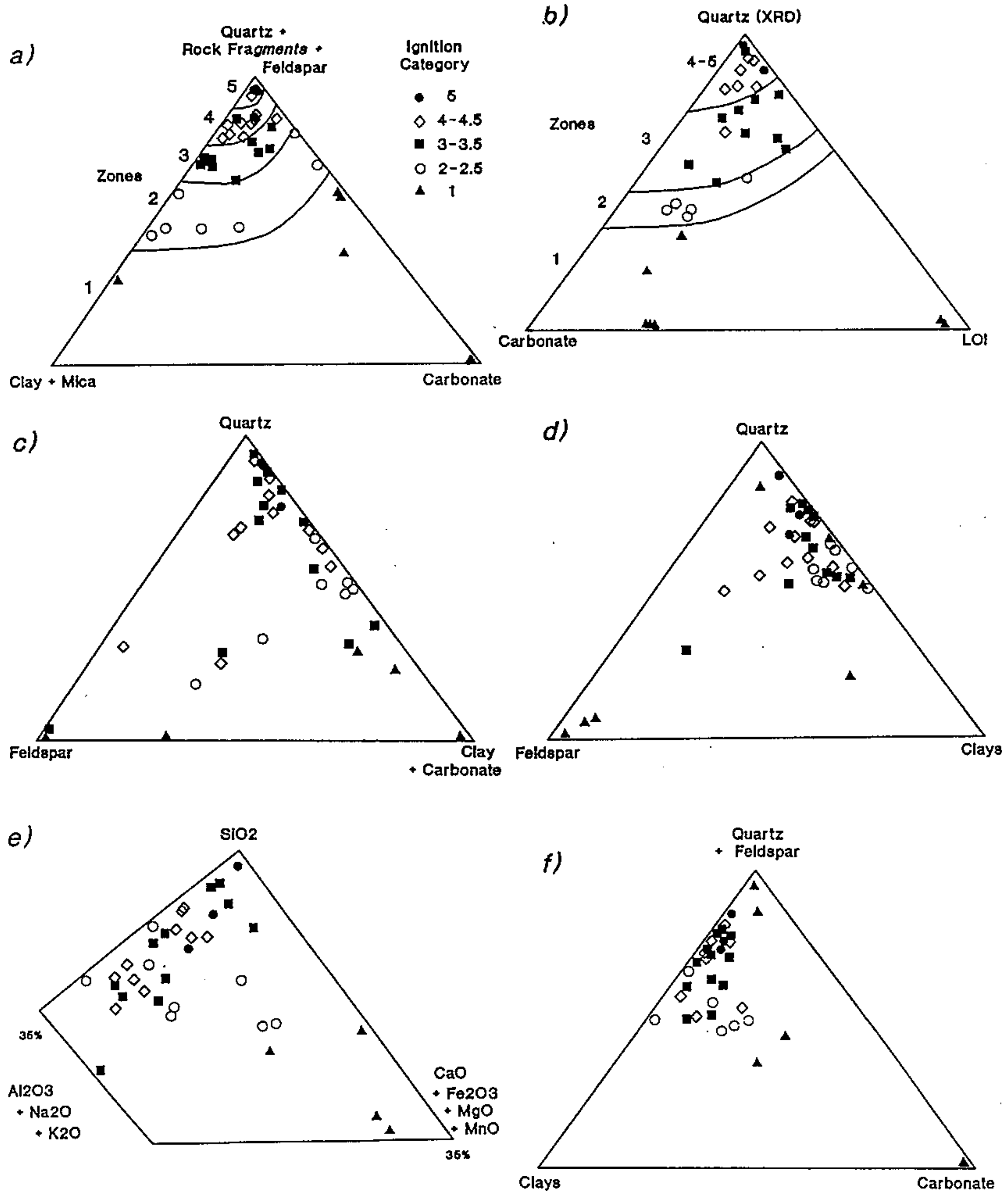


Figure 2.2: Ternary plots showing ignition categorisation (IGCAT) in relation to other rock properties (Ward et al., 1990).

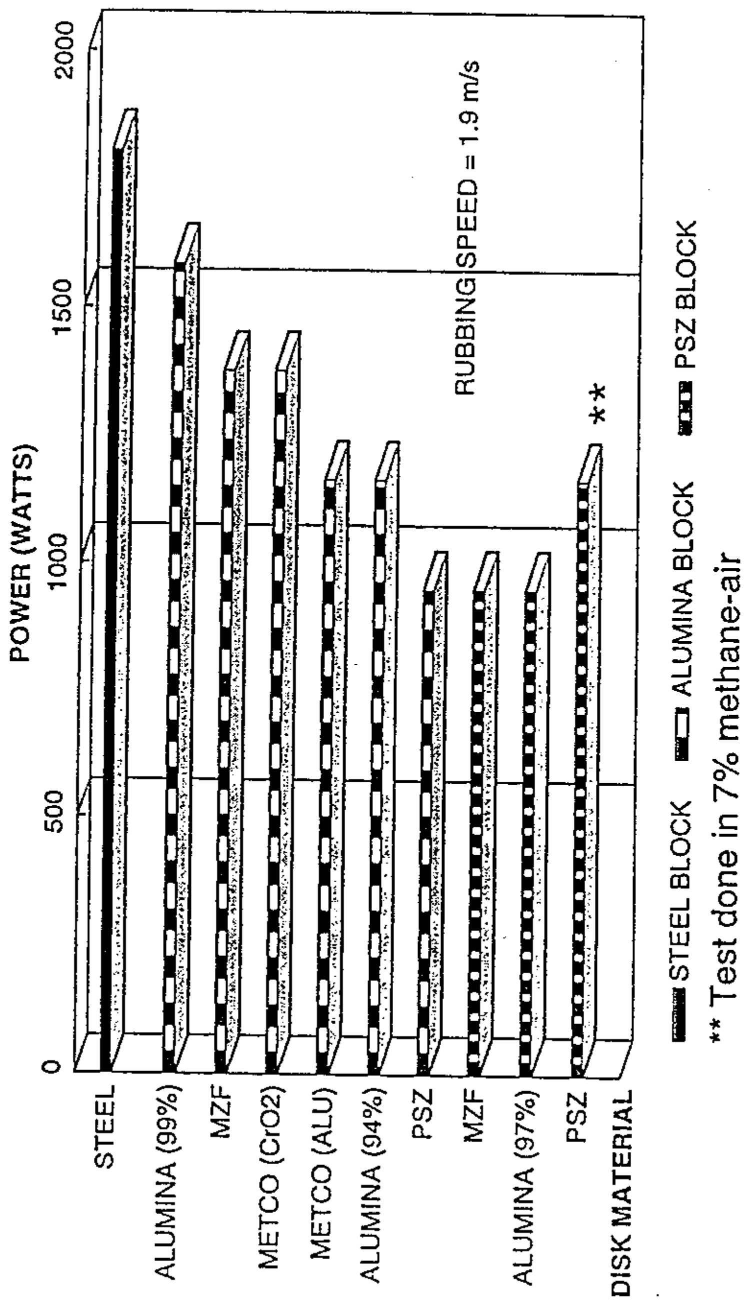


Figure 2.3: Minimum power required to ignite a 15% hydrogen-air mixture from different materials at rubbing speeds of 1.9 $m.s^{-1}$ (Tolson and Brearley, 1995). The results of additional test on partially-stabilised zirconia (PSZ) in a 7% methane-air mixture are also indicated.

Table 2.1: Power required (watts) to ignite 13% hydrogen-air mixture (and with PSZ a 7% methane-air mixture) using different combinations of rotating disk and fixed block materials (Tolson and Brearley, 1995).

Rubbing speed ms^{-1}	Disk Material	Block Material	Igniting Power (Watts)
1.9	MZF	PSZ	950
1.9	Alumina (97%)	PSZ	950
1.9	PSZ	PSZ	**1163**
PSZ vs PSZ tests were done in a 7% methane-air mixture			
1.0	Steel	Steel	1,650
1.0	MZF	Alumina (99%)	1,412
1.0	CrO_2 coated steel	Alumina (99%)	1,412
1.0	Alumina (99%)	Alumina (99%)	1,062
1.0	Alumina (94%)	Alumina (99%)	1,062
1.0	alumina coated steel	Alumina (99%)	950
1.0	PSZ	Alumina (99%)	837
1.0	Alumina (97%)	PSZ	612
1.0	MZF	PSZ	500
0.52	MZF	Alumina (99%)	>981
0.52	Alumina (94%)	Alumina (99%)	799
0.52	PSZ	Alumina (99%)	>734
0.52	Alumina (97%)	PSZ	318
0.52	MZF	PSZ	260

2.4 Design of Mining Equipment

A comprehensive review of frictional ignition research, particularly the processes associated with ignitions from picks on different types of mining equipment, is given in a series of two papers by Powell (1991, 1992). As well as providing a valuable historical account of the development of frictional ignition studies, and in particular British research on the subject, this review incorporates a discussion of the measures which have the potential to minimise ignitions from pick sources in underground coal mining operations. These can be summarised as follows:

1. Provision of good general ventilation, assisted by local ventilation at the machine itself. Even though flammable mixtures of methane/air may still develop, good ventilation will reduce the extent of flame propagation, and hence the overall danger, from any ignition source;

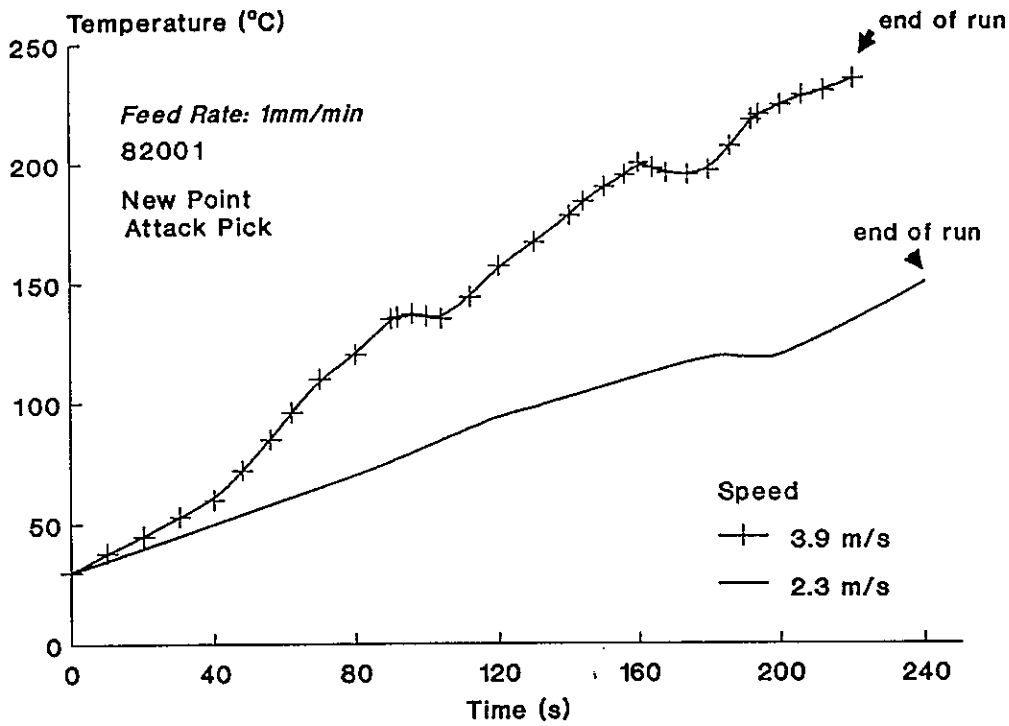
2. Incorporation of low cutting speeds (1.5 and preferably 1 m/s) in mining machine design and operation. This also implies, however, a general reduction in coal production rates;

3. Use of material harder than tungsten carbide, such as poly-crystalline diamond, at the cutting edge of miner picks. Poly-crystalline diamond (pcd) picks, however, must also be designed to protect the tungsten carbide and steel also used in the pick from rubbing against the rock and developing heat that may destroy the pcd itself in the process;

4. Provision of water sprays behind the pick, to quench any hot-spot development that might otherwise lead to methane ignition. Water sprays behind the pick are considered by Powell (1992) to be just as effective for dust suppression as water sprays in front of the pick, and as a by-product are more effective in ignition suppression.

An Australian research study (Lama et al., 1990), carried out partly in conjunction with the University of New South Wales, investigated, *inter alia*, the temperatures developed and the relative likelihood of frictional ignitions associated with contact between several different rock types and several different types of coal cutting picks. Temperatures in these experiments were monitored by a thermocouple inserted near the tip of the respective test picks, as each pick was forced against a rotating wheel of a particular rock type. Although temperatures of over 500°C were recorded (Figure 2.4), ignition itself was difficult to achieve with the equipment used (Ward et al., 1990). The heating rates developed, however, depended on the pick type, the rock type and the cutting speed involved (Table 2.2). Poly-crystalline diamond tipped picks clearly gave lower heating rates, in equivalent conditions, than the tungsten carbide picks used.

A similar approach was taken by Boland et al. (1994) in evaluating the temperatures reached during rock cutting with tungsten carbide pick equipment. Temperature rises to several hundred degrees C were observed over less than one second of cutting time (Figures 2.5 and 2.6). Maximum temperatures of 200°C were obtained from cutter



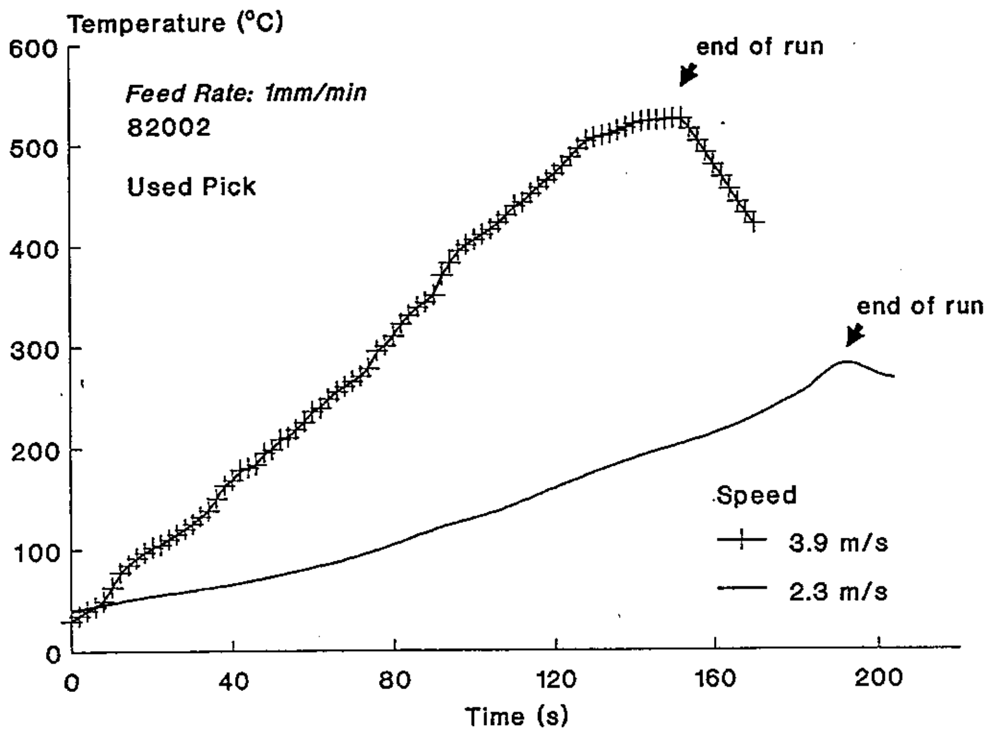


Figure 2.4: variation in temperature with time for different picks on 150 mm sandstone wheel at speeds of 2.3 and 3.9 $m.s^{-1}$, using a constant feed rate maintained by hand (Ward et al., 1990).

picks in pristine condition and up to 460°C from picks ground to simulate contact effects after prolonged wear in cutting operations.

As might be expected, response was most rapid for thermocouples embedded close to the contact surface and significantly delayed, due to heat flow requirements, for thermocouples further away from the contact point. Although actual hot-spot temperatures were not measured, finite-element extrapolation of the data suggested that temperatures of up to 1350°C might be developed at the actual contact point with a new tungsten carbide tool. Such a temperature is consistent with frictional ignition development.

Table 2.2: Rate of change of temperature for various picks on selected rock samples (Ward et al., 1990).

Pick Type	*Rock Type*	*Feed Rate [mm/min]*	*Speed (V) [m/s]*	*Rate of Heating (ΔH) [°C/s]*
New Point Attack	Siltstone	1	2.5 3.9	0.5 1.0
	Mudstone	1	3.9	0.5
	Conglomerate	1	2.3 3.9	1.2 6.0
Used Point Attack	Siltstone	1	2.5 3.9	1.6 3.6
	Mudstone	1	2.5 3.9	0.6 3.6
New Syn. Diamond	Siltstone	1	2.5 3.9	0.12 0.25

Godard et al. (1995) have provided a summary of recent French research into pick design and operation aimed at preventing frictional ignitions in longwall mining operations. This paper reviews the advantages and disadvantages of several different pick designs, including picks with a larger than normal tungsten carbide tip, poly-crystalline diamond tipped picks, and picks with a plasmaturgically-applied tungsten carbide covering over the front and a longer than normal geometric form. It also reviews recent experience with the design of water cooling systems to prevent frictional ignitions in shearer operation, including the provision of a sand filter to ensure a water supply free of suspended matter which would otherwise clog jets installed on the mining equipment.

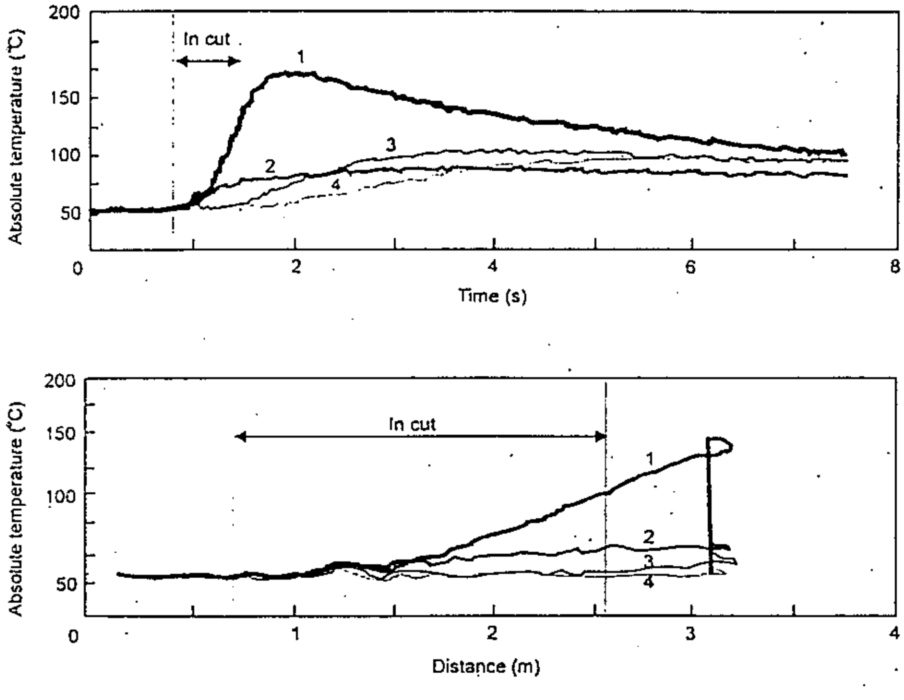


Figure 2.5: temperature rise versus (a) time and (b) distance for a new tool, cutting 14 mm deep at a fast speed. Date from thermocouples at (1) tungsten interface, (2) steel interface, (3) interior axis and (4) interior offset (Boland et al., 1994).

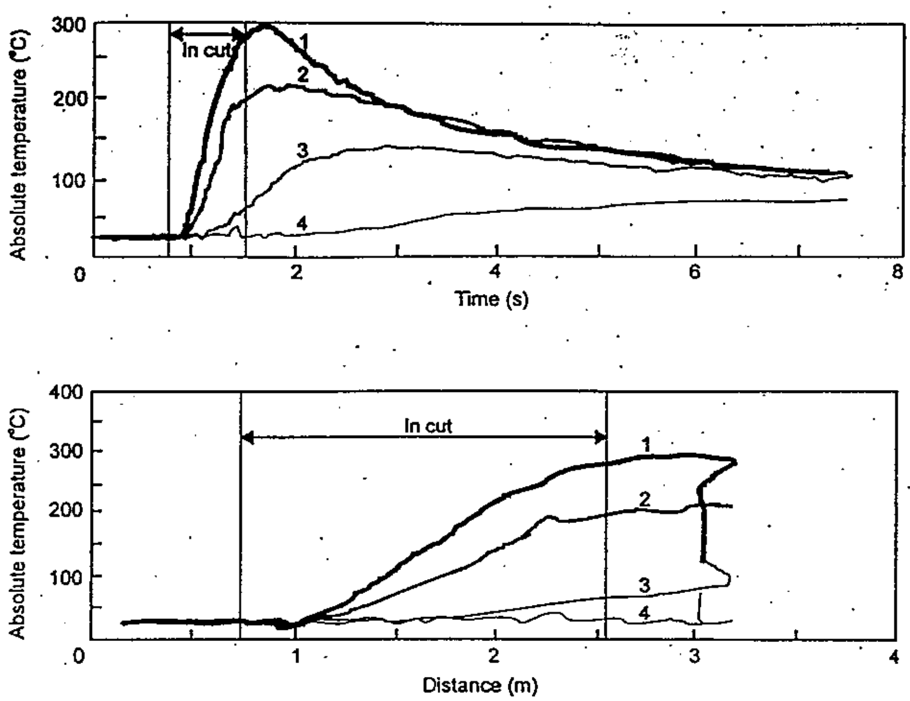


Figure 2.6: Temperature rise versus (a) time and (b) distance for a worn tool, cutting 14 mm deep at a fast speed. Curves numbered as for Figure 2.5 (Boland et al., 1994).

Similar research on the design of mining equipment to minimise frictional ignitions is also currently being carried out by the DMT Gesellschaft fur Forschung und Prufung in Essen, Germany (W-E. Marx and V. May, pers. comm.), including the incorporation of water jets behind the picks on roadheader units. This research is discussed separately elsewhere in the present report.

2.5 Incidence of Frictional Ignitions in Mining

Powell's (1991) review provides data showing that there have been more than 370 reported frictional ignitions of firedamp (methane) in United Kingdom coal mines in the 30-year period between 1960 and 1989 (Table 2.3). Most of these were attributed to machine picks cutting into rock. They include, for example, 24 such ignitions in 1981 and 15 in 1986. Despite the drastic reduction in the number of operating coal mines there were still 11 pick-related ignitions in British collieries during 1989.

A high rate of frictional ignition occurrence has also been reported in US coal mines since the 1960s (Cheng et al., 1987), with a peak of 87 ignitions by machine picks occurring in 1979 (Powell, 1991). Seventy-five percent of the 298 ignitions reported in the USA between 1971 and 1976 were classed as friction induced (Courtney, 1981). Frictional effects are also reported as the largest single cause (38.7%) of methane ignitions in the (former) USSR by Bobrov and Petchenko (1981, quoted by Powell, 1991).

2.5.1 South Africa

Phillips (1995) provides data on 51 ignitions and explosions in South African collieries for the ten-year period between 1984 and 1993 (Table 2.4). These incidents were responsible for 136 deaths and 59 injuries among the mining industry workforce. Three of the most serious were in 1985, 1987 and 1993, with 34, 35 and 53 fatalities respectively.

Friction played a dominant role as a causative factor in these incidents, being responsible for 32.5% of all occurrences and 68% of the ignitions and explosions for which causes have been established. Most occurrences (55%) were in bord and pillar workings (Table 2.5), with lesser proportions in longwall panels, goaf areas and non-face situations.

The frequency of frictional ignitions in South Africa from continuous miners has increased steadily since the introduction of this equipment in the early 1970s. The increase has been accompanied by a related decrease in the frequency of ignitions caused by blasting (Table 2.6). Despite the related decline in the use of coal cutters, however, the frequency of ignitions from coal-cutter picks has paradoxically increased, rather than decreased, with the change to continuous miner systems. This may reflect complacency and lack of care among operators, due to the small area of rock actually exposed at any one time to the cutting process.

Table 2.3: Reported ignitions of firedamp (methane) in United Kingdom Coal Mines (after Powell, 1991).

Year	*Shot Firing*	*Elect-rical*	*Mechan-ical*	*Other*	*TOTAL*
1960	6	1	14	5	26
1961	7	2	8	4	21
1962	6	4	8	1	19
1963	4	3	8	4	19
1964	7	3	10	3	23
1965	7	2	9	2	20
1966	7	1	23	2	33
1967	5	2	14	2	23
1968	2	2	21	2	27
1969	4	3	19	2	28
1970	3	2	17	0	22
1971	1	1	13	0	15
1972	2	1	5	1	9
1973	1	2	17	0	20
1974	7	1	18	0	26
1975	3	0	13	2	18
1976	0	1	14	0	15
1977	2	1	24	0	27
1978	0	0	11	1	12
1979	1	1	12	1	15
1980	1	2	14	0	17
1981	2	1	24	1	28
1982	0	0	7	0	8
1983	0	1	5	0	6
1984	0	0	3	0	3
1985	0	0	3	0	3
1986	0	0	15	1	16
1987	0	1	12	1	14
1988	0	0	6	0	6
1989	0	0	11	1	12

Table 2.4: Ignition and explosion frequency in South African coal mines, 1984-1993 (Phillips, 1995).

YEAR	IGNITIONS		EXPLOSIONS		
	NO	INJURED	NO	INJURED	KILLED
1984	5	0	2	0	6
1985	6	1	1	7	34
1986	2	-	0	-	-
1987	1	-	1	11	35
1988	1	1	1	5	0
1989	4	0	1	4	1
1990	7	0	2	13	0
1991	5	1	1	17	1
1992	5	1	1	2	6
1993	4	0	1	0	53
TOTAL	40	4	11	59	136

Table 2.5: Location of incident epicentres in South African underground collieries, 1982-1993 (Phillips, 1995).

LOCATION	IGNITIONS	EXPLOSIONS	TOTAL	% TOTAL
FACE AREA:				
Bord and Pillar	25	10	35	55
Longwall Development	4	0	4	6
Longwall (Face)	3	0	3	5
ABANDONED AREAS:				
Pillar Extraction Goaf	2	3	5	8
Longwall Goaf	1	0	1	1,5
NON-FACE AREAS:				
Intake Airways	0	2	2	3
Return Airways	0	2	2	3
Shaft Areas	0	1	1	2
UNKNOWN	11	0	0	16,5

Table 2.6: Changing pattern of ignition sources in South African collieries (Phillips, 1995).

IGNITION SOURCES	PERIOD							
	1960s		1970s		1980s		1990 to 1992	
	I	%	I	%	I	%	I	%
CM Picks	0	0	1	5,5	14	29,5	6	25,5
CC Picks	1	4,5	3	17	11	22,5	0	0
Shearer Picks	0	0	0	0	1	2	0	0
Stone on Stone	0	0	0	0	4	8	1	4
Blasting	14	64	6	33,50	5	10	1	4
Spon Comb	0	0	0	5,5	0	0	2	8
Heated Surface	1	4,5	1	5,5	1	2	0	0
Naked Flame	2	9	1		0	0	0	0
Electricity	2	9	2	11	5	10	0	0
Lightning	2	9	4	22	3	6	0	0
UNKNOWN	0	0	0	0	5	10	14	58,5
TOTAL	22	100	18	100	49	100	24	100

I = number of incidents of ignitions/explosions

Phillips (1995) indicates that South African coals are significantly harder than average, requiring powerful machines operating at relatively high drum rotation speeds to achieve acceptable production levels. No information, however, seems to be available on the relative incendivity of South African coal mine rocks, with which the different ignitions are associated. Given the similarity of the geological setting to those of the Permian coal measures in eastern Australia, however, some comparative studies of rock incendivity may be useful.

2.5.2 New South Wales

Although ignitions due to naked flames and shotfiring were relatively common before that time, the first recorded occurrence of methane ignition by friction in New South Wales coal mines seems to have been at Redhead Colliery in 1926. There is, however, some uncertainty about this occurrence, since the actual ignition was ascribed at the time to either a naked flame or a roof fall.

Friction as a cause of ignition does not seem to have become apparent again until 1950 (Ward et al., 1990), and only since about 1971 has friction regularly been reported among the causes of methane ignitions in New South Wales coal mines.

A comprehensive report dealing with the location and cause of 23 separate frictional ignitions of methane in New South Wales collieries between July, 1987 and December, 1993 was prepared by the New South Wales Department of Mineral Resources and circulated to the industry in July, 1994. Of the incidents reported (Tables 2.7 and 2.8), 12 were associated with continuous miner drum picks and 4 with longwall shearer drum picks. Other causes were more diverse, and these are discussed more fully below.

Of the 23 ignitions covered by the Mineral Resources report, 16 (or 70%) involve picks of shearers or continuous miners interacting with rock material above, below or within the coal seam. Seven ignitions involve the interaction of picks with the hard, lithic conglomerates of the Newcastle Coal Measures and one involves interaction between picks and sandstone in the same general sequence of roof strata. Conglomerate from this area, tested by Ward et al. (1990) appears to be a highly incendive (IGCAT 4 to 5) rock type. Extraction should clearly proceed with caution where methane emissions are likely in association with these particular strata.

The next most common type of ignition appears to arise from interaction between miner picks and siliceous nodules or bands within the actual coal seam. Other types of intra-seam material, described in the report by the Department of Mineral Resources (1994) as "conglomerate" in one instance and a "stone intrusion" in another, are also involved in two of the ignitions reported. Such intra-seam incendive materials are inherently more difficult to identify and predict than more persistent and easily recognisable conglomeratic roof layers. They are also more widespread, having produced ignitions both in the Southern and the Hunter Coalfields during the period under review.

The most recent occurrence of this type, an ignition at South Bulga in November, 1993, was investigated more fully by the UNSW project team as part of the present study. The material responsible for the ignition in this instance appears to have been a siliceous horizon within the seam, immediately beneath a prominent claystone band. This horizon was apparently formed by silicification of the porous organic matter (peat) at an early stage of seam development. Its petrographic character and its (high) frictional incendivity are discussed more fully in other sections of the present report.

The remaining seven ignitions reported by the Department of Mineral Resources were ascribed to a variety of causes. These included metal-on-metal friction associated with drilling for roof bolts (2), rock pressed against a rotating metal shaft in a mining machine (1), sparks falling into a shaft from welding operations (1), and electric arcing developed from cable damage associated with rib collapse in pillar extraction (1). Although the evidence is perhaps less clear-cut, the remaining two ignitions appear to represent rock-on-rock interactions, associated with either shaft infilling or with an apparent goaf fall.

Table 2.7 : Summary, by date, of reported frictional ignitions in New South Wales coal mines, July, 1987 to December, 1993.

Mine	Date	Equipment		Strata				Remarks
		Miner or Shearer	Other	Roof	Floor	In-seam	Other	
Lemington No 1 u/g	11/08/87		*				*	Rock on shaft coupling
Munmorah State	15/09/88	*		*				Picks on conglomerate roof
Munmorah State	01/02/89	*				*		Picks on conglomerate in coal face
Myuna	04/04/89	*		*				Picks on conglomerate roof
Munmorah State	28/06/89	*		*				Picks on conglomerate roof
Cordeaux	22/07/88	*					*	Picks on fallen roof rock
Munmorah State	19/04/89		*	?			*	Fire apparently from goaf fall
Teralba	20/07/89		*				*	Sparks from burning fell into shaft
Lemington	01/08/89		*				*	Drilling through steel roof strap
Kemira	01/03/90	*				*		Picks on quartz nodule in seam
Ellalong	24/09/90		*				*	Drill struck steel roof strap
Kemira	03/10/90	*				*		Picks on siliceous nodule in seam
Appin	05/10/90	*			*			Picks on sandstone lens in floor
Kemira	01/12/90	*				*		Picks on siliceous nodule in seam
Munmorah State	27/12/90	*		*				Picks on sandstone roof
Appin	08/02/91		*				*	Electric arc induced by fall
Munmorah State	14/07/92	*		*				Picks on conglomerate roof
Munmorah State	06/08/92	*		*				Picks on conglomerate roof
Teralba	26/08/92	*				*		Picks on stone intrusion
Seaham No 2	14/12/92		*				*	Filling shaft with building material
Cooranbong	28/04/93	*		*				Picks on conglomerate roof
Cooranbong	07/05/93	*		*				Picks on conglomerate roof
South Bulga	26/11/93	*				*		Picks on siliceous band in coal #

Note: Originally reported as picks on hard section of intra-seam claystone band

Table 2.8 : Summary, by type, of reported frictional ignitions in New South Wales coal mines, July, 1987 to December, 1993.

Mine	Date	Equipment		Strata				Remarks
		Miner or Shearer	Other	Roof	Floor	In-seam	Other	
Ellalong	24/09/90		*				*	Drill struck steel roof strap
Lemington	01/08/89		*				*	Drilling through steel roof strap
Appin	08/02/91		*				*	Electric arc induced by fall
Seaham No 2	14/12/92		*				*	Filling shaft with building material
Munmorah State	19/04/89		*	?			*	Fire apparently from goaf fall
Munmorah State	01/02/89	*				*		Picks on conglomerate in coal face
Cooranbong	07/05/93	*		*				Picks on conglomerate roof
Cooranbong	28/04/93	*		*				Picks on conglomerate roof
Munmorah State	15/09/88	*		*				Picks on conglomerate roof
Munmorah State	14/07/92	*		*				Picks on conglomerate roof
Munmorah State	28/06/89	*		*				Picks on conglomerate roof
Munmorah State	06/08/92	*		*				Picks on conglomerate roof
Myuna	04/04/89	*		*				Picks on conglomerate roof
Cordeaux	22/07/88	*					*	Picks on fallen roof rock
Kemira	01/03/90	*				*		Picks on quartz nodule in seam
Appin	05/10/90	*			*			Picks on sandstone lens in floor
Munmorah State	27/12/90	*		*				Picks on sandstone roof
South Bulga	26/11/93	*				*		Picks on siliceous band in coal #
Kemira	01/12/90	*				*		Picks on siliceous nodule in seam
Kemira	03/10/90	*				*		Picks on siliceous nodule in seam
Teralba	26/08/92	*				*		Picks on stone intrusion
Lemington No 1 u/g	11/08/87		*				*	Rock on shaft coupling
Teralba	20/07/89		*				*	Sparks from burning fell into shaft

Note: Originally reported as picks on hard section of intra-seam claystone band

3 FORCE AND TEMPERATURE MEASUREMENT

3.1 Introduction

The ignition categorisation developed for the previous UNSW project (Ward et al., 1990, 1991a,b) was based essentially on empirical observation. Although experimental work was performed in a systematic manner, the methods used could not quantify, except in relative terms, the physical phenomena such as force and temperature associated with the frictional ignition process. This was felt to be a fundamental limitation if a standard test was to be developed or if frictional incendivity was to be predicted on the basis of rock mineralogy and texture.

As indicated above, a certain amount of quantitative data was obtained in the course of the 1987-1990 project, as a by-product of the main investigation, on the rate of heat development during metal-on-rock friction (Ward et al., 1990; Lama et al., 1990). Thermocouples inserted a short distance behind the cutting edge of miner picks pressed against a series of rotating rock wheels showed different rates of heat development for the several different pick types and rock types evaluated. The temperatures in question, however, were no more than about 200°C, and in themselves were well below those required for ignition of methane. This was largely due to the fact that the thermocouples were necessarily separated from the actual contact point be a few millimetres of metal, and unlike the methane in a mine atmosphere were not directly in contact with the hot-spot involved. Higher temperatures, producing red-heat and white-heat conditions, were clearly developed at the contact points. Although useful in establishing relative heating rates, this approach did not directly provide data on the actual temperatures leading to the gas ignitions sometimes observed.

A series of empirical tests was also carried out, in the 1990 investigation, to test the effects of different rubbing forces on the frictional ignition process. The results, however, were inconclusive, due to the relatively primitive methods used for force measurement and the fact that static and not dynamic loads were being monitored by the test procedure. Similar limitations applied to the study of PSZ and other ceramic materials by Tolson and Brearley (1995).

In the light of these limitations, a major part of the work program for the present project was to modify the test rig and develop instrumentation to monitor the forces and temperatures actually built up at the contact surface during the frictional ignition process. This part of the study involved the following components:

1) Design and construction of a pick-force dynamometer to measure the lateral and normal forces developed during rock friction, including friction where gas is present and ignition results;

2) Selection and use of a non-contact pyrometer, with electronic output, to monitor the temperatures developed, under different test conditions (including tests to ignition in a methane atmosphere), at the active contact point;

3) Development of data acquisition and processing hardware and software to capture, produce and display continuous records of both force and temperature during routine ignition tests;

4) Co-ordination of the time-varying force and temperature data with observational (videotape) records of each test run, through development of methods to synchronise video recordings with the temperature/force output system.

A separate but equally important aspect of the instrumentation for the project was the removal and re-installation of the Horiba gas analysis facility in the UNSW Department of Mining Engineering to the same laboratory as the frictional ignition test rig itself. This provided a considerable improvement in the efficiency of the ignition testing process. The gas analyser had been located one floor above the main project laboratory for the previous (NERDDP) investigation, requiring the use of at least two people and an extensive intercom system to introduce the appropriate gas concentration to the rig's ignition chamber.

3.2 Pick Dynamometer Design

One of the primary aims of the frictional ignition project was to establish some real values on the rubbing frictional forces involved when a rock slider is place against a rotating rock wheel cut from the same rock.

This necessitated the design of instrumentation which could measure and record orthogonal forces associated with the rotating wheel and slider. The crux of this part of the instrumentation was to develop a small force transducer robust enough to withstand the rigours of the explosion chamber and sensitive enough to measure the level of forces encountered. The transducer would also need to have a high natural frequency so that the response to rapid changes in forces could still be measured.

This project was able to utilise the design of such a force transducer from a cone dynamometer developed by one of the researchers, Drago Panich, as part of a previous research project at Newcastle-upon-Tyne.

3.2.1 *Design Criteria*

There were two basic considerations for the design of a pick dynamometer for this project.

- Restriction on Size

As the dynamometer was to be placed in a relatively small chamber and had a restricted mounting area where it could be positioned, size restriction for the unit was a significant consideration.

- Capability

The dynamometer had to be capable of sensing 3 orthogonal forces and at the same time reasonably robust, such that the sensing mechanism was not damaged by explosions, disintegrating rock fragments, chipping from wearing wheels or excessive vibration.

The transducer design, provided it met these specifications was also required to be cost effective. A design using strain gauges was therefore selected. Although the manufacture of any transducer involving strain gauges can involve significant expenditure, the amounts are only a fraction of the cost associated with piezoelectric sensing materials such as thin quartz crystal sections

3.2.2 *General requirements*

A succinct statement has been made by Boothroyd (1965) when describing the requirements for a metal cutting dynamometer:

> *"It is essential that the instrument should have high rigidity and high natural frequencies so that the dimensional accuracy for the cutting operation is maintained and the tendency for chatter vibrations to occur during cutting operations is minimised. The dynamometer must, however, give strains or displacements large enough to be remeasured accurately."*

Rapier (1959) is also quoted by Boothroyd as suggesting displacement ratio (v_d) and tool displacement being used to measure dynamometer efficiency.

$$v_d = \frac{y}{x}$$

Where:

v_d = displacement ratio
y = displacement measured by gauge or transducer
x = tool displacement

If the tool displacement is kept as small as possible in the dynamometer design then geometric considerations are minimised during operation of the transducer. This can be achieved by having a rigid design and/or material of high stiffness. Such a design will give a dynamometer of high natural frequency.

The other parameter in the v_d ratio is y, the displacement measured by gauge or transducer. This should be as large as possible to give maximum output from the instrumentation. Generally x and y are not mutually exclusive, and the effect of high rigidity may also reduce the output from the transducer to unacceptable levels.

However, by continuing the optimum requirements of y one should try to make the value of v_d as large as possible. In most designs the value of v_d cannot be greater than unity. A design where v_d approaches unity generally corresponds to an efficient design.

Other considerations involve use of clamped or bolted joints, pivots or hinges of any kind. These should be avoided at all costs, due to possible hysteresis effects caused by friction. For this reason a dynamometer should always be manufactured if at all possible from a single block of material.

When referring to rock cutting dynamometers some of the above points are also stated by Dalziel et. al. (1968), particularly with regard to minimum deflection of a tool under load when cutting into rock material. Dalziel et. al.(1968) also give a rule of thumb for the natural frequency response for a rock and coal cutting dynamometer as being some 100 Hz per 1 ft/min of cutting speed.

The major differences when comparing rock cutting dynamometers and the application used in the present research program are the level of forces exerted by the rubbing friction of the rock slider and the rotating rock wheel. One would therefore expect a natural frequency of 110,000 Hz at the highest rock wheel speed of 700 rpm (1100 ft/min) currently used on the frictional ignition rig. This seems, however, to be rather high by at least a factor of ten. Dalziel et. al. (1968) also point out the conflict between high natural frequency and rigidity with high sensitivity, adding that sensitivity should be large enough to allow recording of signals without excessive amplification.

An ideal three orthogonal force dynamometer should not have any interaction (ie. cross-influence) between the individual values of each measured component. This of course does not generally occur in practice, due to slight misalignment of gauges and cross sensitivity.

Several types of dynamometer have been used in mechanical rock cutting research, including the following :

1. Cranked - bar
2. Cranked - beam
3. Solid plate
4. Diaphragm
5. Plate and cylinders
6. Parallel bar

Figure 3.1 represents the normal plate dynamometer used with most linear shaping machines involved with rock cutting, and is also similar to one used with high pressure water jet research.

Piezoelectric dynamometers were also considered, and one Kistler design in particular was thought to be suitable. The cost, however, was in the region of $25,000. This in itself was unacceptable, coupled with the fact that areas of uncertainty existed as to

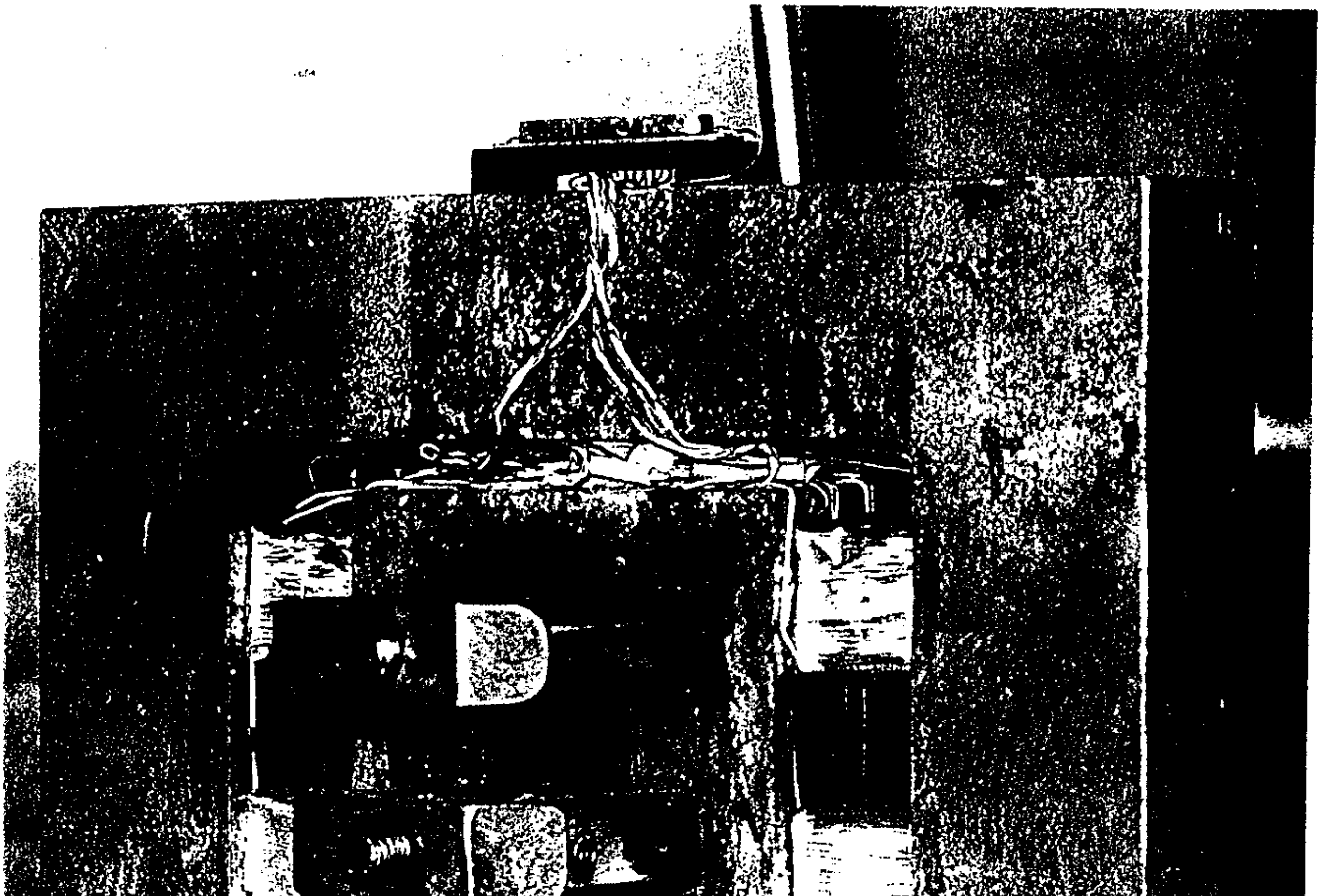


Figure 3.1: Linear shaping machine plate dynamometer.

whether such dynamometers were a sufficiently robust and practical option for the particular application intended.

3.2.3 *Cone sensing shell dynamometer*

As stated previously the size limitations reduced the possible geometric shapes and types of dynamometer that could be considered for the present project, particularly because of the inherent conflict between sensitivity and strength.

The principal criteria which led to the choice of a conical shell design were:

- The inherent rigidity of a cone geometry.
- Reduction of the bending moments due to cutting and sideways forces by having a sensing area close as possible to applied forces.

Figures 3.2 and 3.3 show the cone-sensing shell design, respectively without and with the cover, and the first design for the rock specimen holder.

Essentially the principle involved strain gauging a conical shell attached by thread and lock screw to a hollow shank section. This shank was then fastened on to the rock slider carriage fabricated for the previous project by means of bolts.

Strain guage arrangements are shown diagrammatically in Figure 3.4, and Appendix B shows the dimensions of the cone dynamometer. Strain gauging involved the use of parallel gauges (EA-06-125-PC-350) to measure radial (frictional and sideways) forces and rosette gauges (CEA-06-125WT-350) to measure axial forces.

The radial bridges were placed about the neutral axis 90 degrees apart such that they would be able to measure bending due to a particular radial force and have, theoretically, zero interaction with the other orthogonal component.

The axial bridges (4 pairs of rosettes) were situated at 45 degrees to the radial gauges

It must be stressed that the cone dynamometer was built to test a design concept. Therefore a minimal attempt has been made at this point to optimise sensitivity and to calculate the maximum stress capabilities of the shell. Calibration tests of the earlier cone dynamometer developed at Newcastle-upon-Tyne indicated that the force levels expected during the projected frictional tests could be accommodated by the current model design.

The difficulty involved with theoretical calculations was the uncertainty as to whether the cone would behave as a thin shell or in a similar manner to a thick cylinder. Although the approach tends to be an empirical one, the cone design does, however, enable the relevant calibration curves to be reproduced.

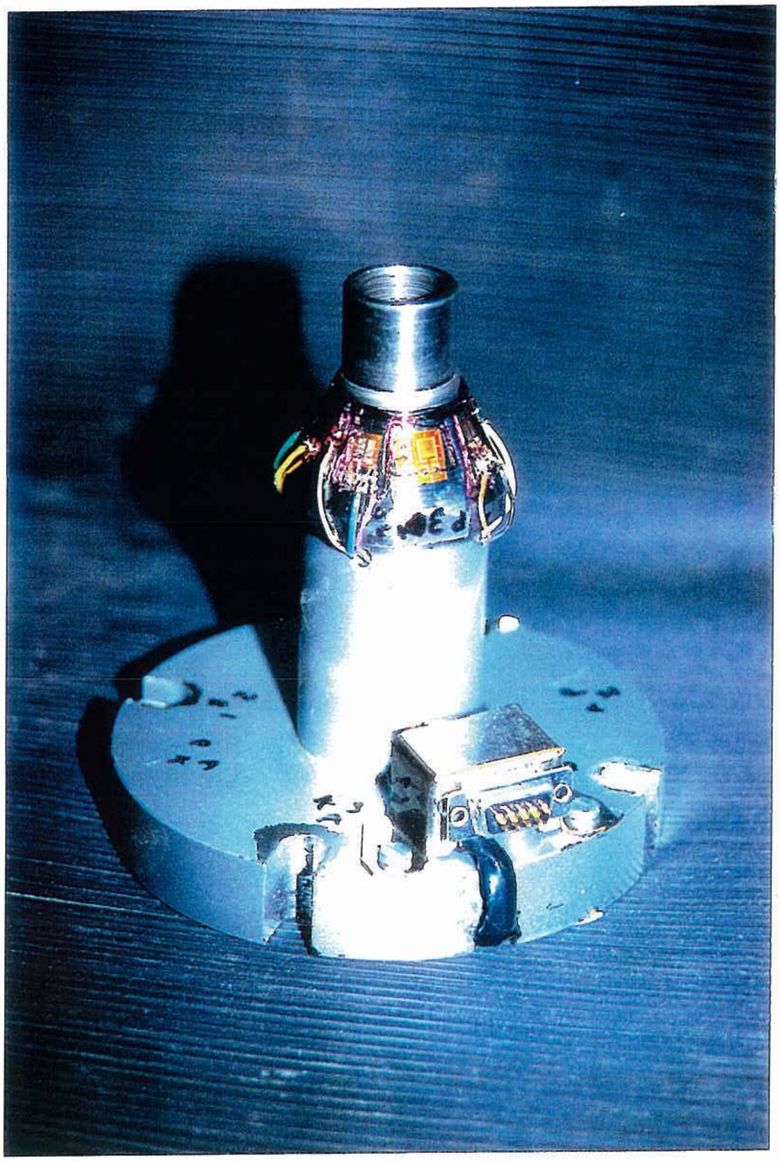


Figure 3.2: Cone-sensing shell dynamometer.

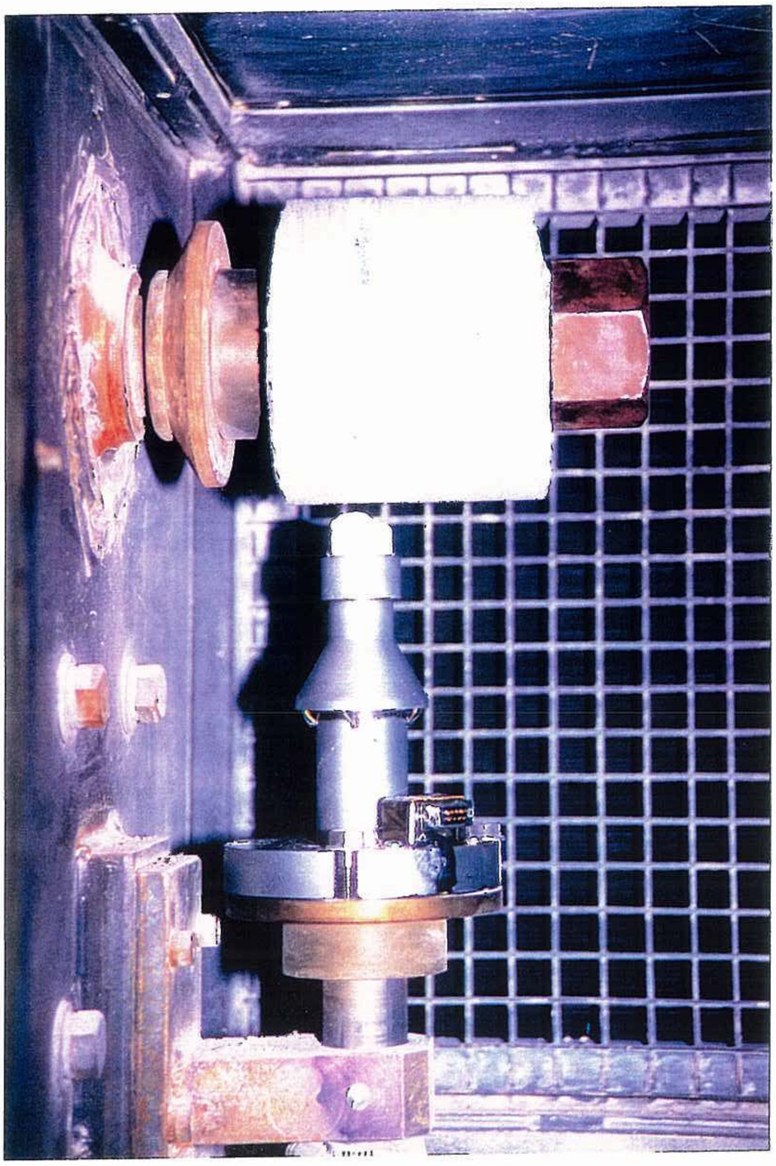
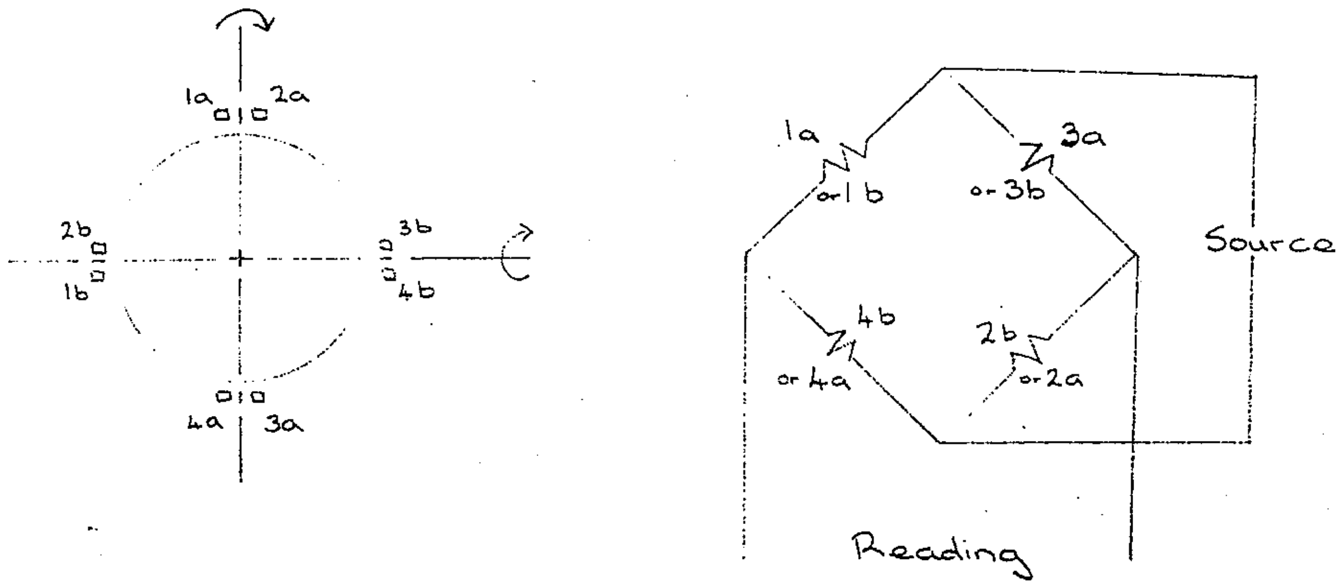
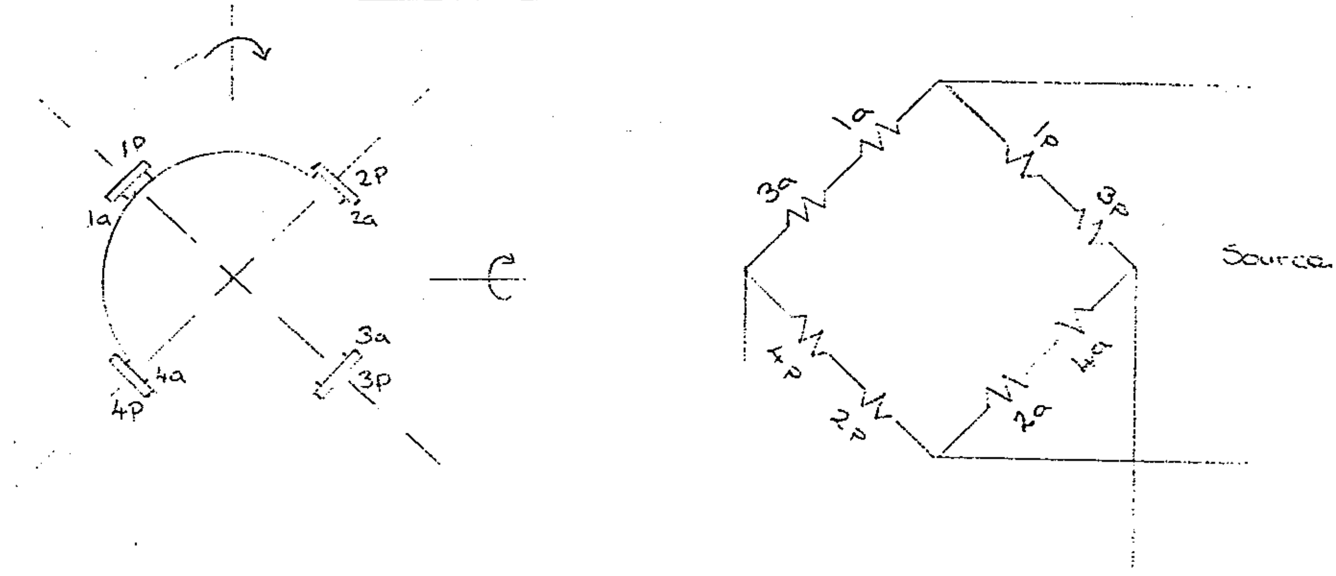


Figure 3.3: Cone-sensing shell dynamometer, fitted with cover, showing the first design for the rock specimen holder (compare to Figure 3.5).



<u>Radial Bridge Arrangements</u>



<u>Axial Bridge Arrangement</u>

Figure 3.4: Strain guage arrangements on cone dynamometer.

The idea of a cone was also reinforced by Boothroyd (1965), who found that a tapered cantilever dynamometer design gave a good combination of high natural frequency and natural stiffness.

3.2.4 *Specific operational and development factors*

The development of the cone dynamometer for use in the frictional ignition project high lighted two factors in its performance, zero drift and rebound effect, as well as the need for a high level of skill when initially installing the strain gauges.

Initial installation of the strain gauges presented learning experiences for the workshop craftsman, as positioning, gluing, curing and finally maintaining a good contact in the solder joint for the amplifier wires required several attempts before a repetitive response could be obtained. The signals from all the bridges were available before the installation of the infra red pyrometer equipment (see below), and a number of initial tests involving force but not temperature measurement were carried out.

During these initial evaluation trails, however, when all the data acquisition equipment installed, the sideways-force strain gauge bridge became unserviceable. Data from this bridge were not, however, strictly neccessary for the frictional ignition program, as the main force measurements required were only those involving the frictional and normal forces. It was decided to continue testing with only these two strain gauge bridges in operation, thus avoiding delays in testing programme. A two-dimensional and not a three-dimensional stress measurement system was therefre used for the bulk of the project work.

The dynamometer, installed on the test rig, is illustrated in Figure 3.5.

The testing programme identified two effects from the dynamometer which were to require more detailed investigation. These were a zero drift and a rebound effect.

Zero drift is represented by a persistent difference in the output level obtained from the normal force strain gauge bridge before and immediately after a test has been completed. The stress level indicated by the strain gauge bridge was invariably higher, in routine testing, after the normal force had been removed than it was before the force was applied and the test run. This particular bridge used rectangular rosettes and measured a Poisson's ratio effect, rather than bending as was the case with the frictional force bridge. The output therefore also needed significantly more amplification. It is believed that the zero drift effect was caused by heating of the cone dynamometer during testing, as the strain gauge bridge output tended to stabilise close to the original output some time after each test had been completed. There was not the same zero drift on the frictional force bridge, presumably because the heat effect did not induce bending in the dynamometer shaft.

The duration of the frictional ignition tests allow in some cases for substantial heating of the dynamometer, and further work is warranted to evaluate the effects of this heating process.

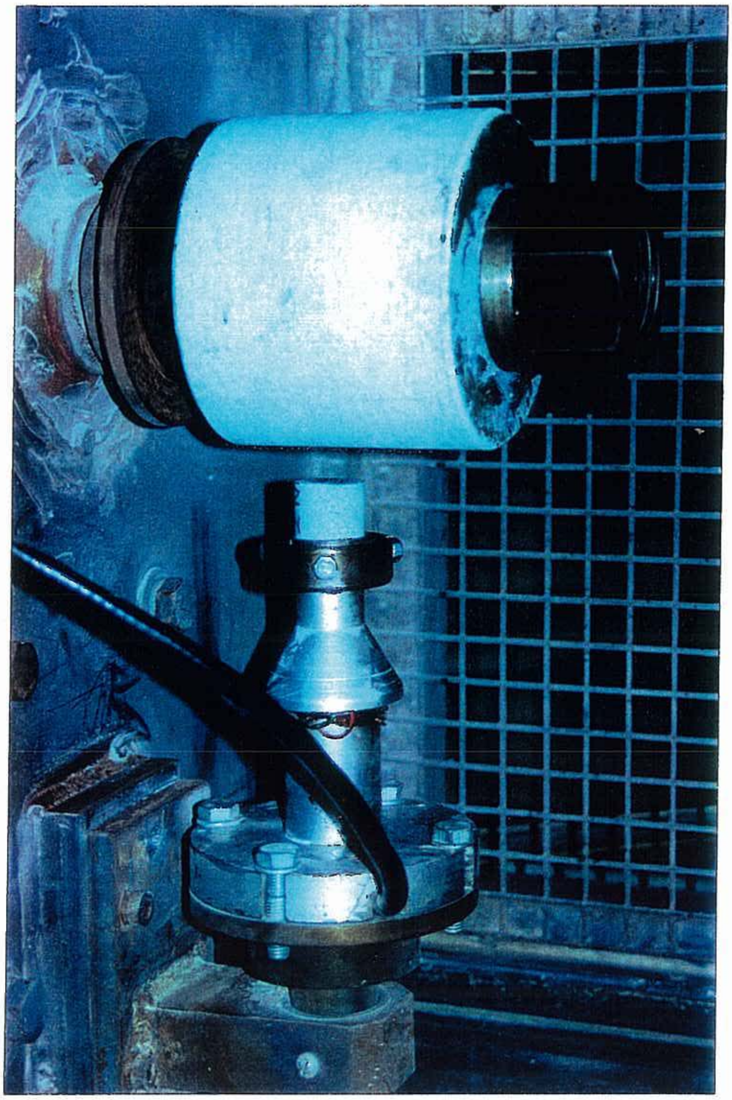


Figure 3.5: Photograph illustrating the dynamometer installed in the test rig, with a small cylindrical rock specimen attached to the top as a slider. A 150 mm diameter rock wheel can be seen above the dynamometer installation.

A negative change in the stress level indicated by the frictional force strain gauge bridge was also commonly noted immediately after an ignition explosion. This has been termed rebound effect. Its probable cause is the impact of the physical blast on the mass of the slider assembly that carries the cone dynameter and the small rock sample.

The only other operational parameter that needs to be noted is that, if other materials of different sizes such as picks were to be placed in the dynamomometer sample holder, rather than a cylindrical rock slider, a new set of calibration curves would be required.

3.2.5 *Other potential applications*

Further application in the mining industry of this type of force dynamometer design are:

- Development as a sensor for coal cutting in longwall operations to determine roof and floor horizons
- Monitoring of ripability in open cut coal operation to determine machine performance and variability of the rock.

3.3 Temperature Measurement Instrumentation

The temperature of the 'hot spot' on the rotating rock wheel was monitored using a two-colour infrared thermometer system. This comprised a Mikron Instrument Company M77LS temperature transmitter or 'Infraducer' and an M77EM module for power supply and signal conditioning.

The Infraducer, type M77LS 0700-2000 CRL1, remotely measures temperatures between 700 and 2000 degrees Celsius and provides a 4-20 mA linear output. It utilises the two-colour principle in which the temperature measurement is derived from the ratio of the radiation intensities of two adjacent wavelengths rather than from absolute intensity as with single colour (single band) instruments. Two-colour thermometry affords the following advantages which make it particularly suitable for measuring a moving 'hot-spot' within the explosion chamber.

- Readings are independent of emissivity.
- They are unaffected by dust and other contaminants within the field of view or by dirty viewing windows.
- They are independent of target size and unaffected by a moving target within the field of view.

The Infraducer was tripod mounted and equipped with through-lens sighting and variable focussing to facilitate pinpointing on the 'hot spot' (Figure 3.6).

For the duration of the program of explosion chamber testing, the response was set to 'downscale burnout', i.e. the output defaulted to a low fixed value whenever the minimum conditions for a valid measurement were not met, and the response time was set to the fastest possible (40 ms).

The 4-20 mA output from the Infraducer was converted to a 1 V/ °C signal by the power supply and signal conditioning module type M77EM 0700-2000C-00Y0. As the system was required to respond to rapid temperature fluctuations, the 'peak/valley picker' circuitry was bypassed by setting its control switch to 'cancel'.

A schematic diagram indicating the use of both the pyrometer and the dynamometer in data acquisition is given in Figure 3.7.

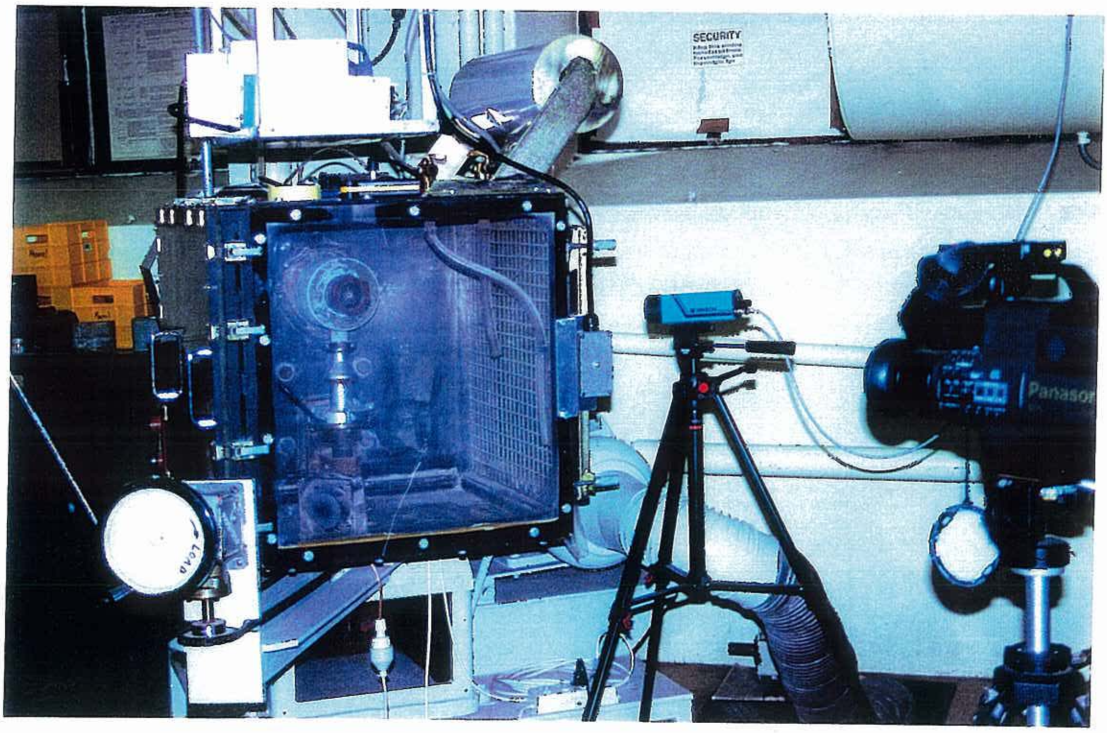


Figure 3.6: Photograph showing the tripod-mounted pyrometer unit (Infraducer) in relation to the gas chamber of the test rig. A video camera used for recording details of each test is visible in the foreground.

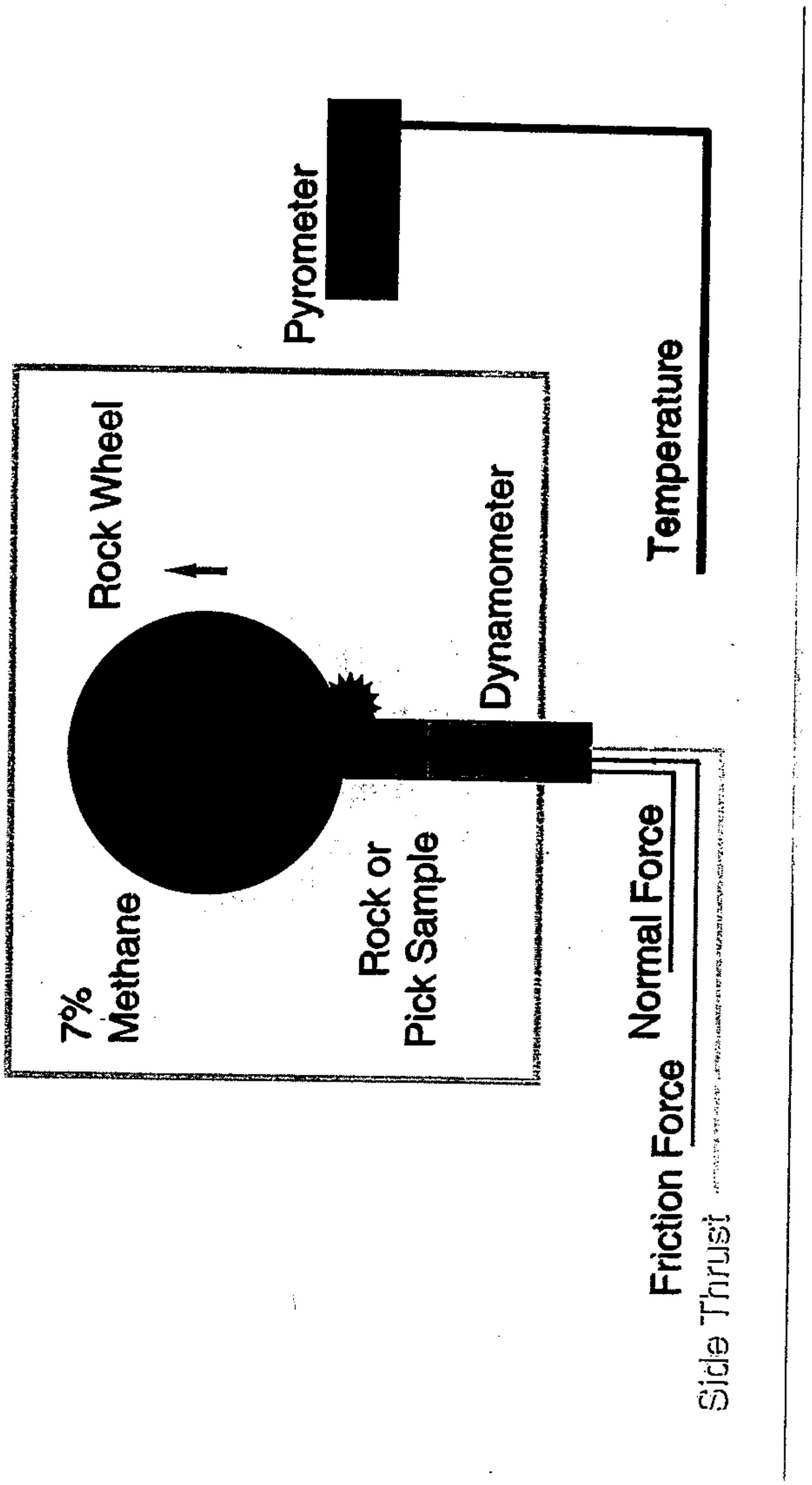


Figure 3.7: Schematic diagram illustrating the use of the dynamometer and the pyrometer system as the basis for force and temperature data acquisition in frictional ignition experiments.

3.4 Computerised data acquisition

3.4.1 *Hardware*

Data acquisition and timing for the Frictional Ignition Test Rig was provided via an Apple Macintosh Quadra 840AV personal computer with a National Instruments NB-MIO-16XL-42 input/output board, installed in a NuBus slot (no. 4), together with an SCXI front-end signal conditioning extension.

The instrumentation front-end system comprised an SCXI-1000 chassis fitted with an SCXI-1121 4-channel signal conditioning module. The chassis housed the latter, supplied power and controlled the data and control lines of the SCXI bus.

In order to maximise noise rejection in the connecting cable, the SCXI system was located as close as practicable to the explosion chamber. Shock and vibration isolation was ensured by mounting the system in racking suspended from the ceiling and located so as to avoid blast effects and contamination by explosion products.

The SCXI-1121 module provided strain gauge excitation and signal conditioning for the dynamometer. The fully isolated excitation channels each comprised a 3.333 volt source with overload protection and current limiting. Each analogue input channel included an isolated amplifier and a 3-pole RC low-pass antialiasing filter set at 10 kHz. Channels 0 to 2, corresponding to the dynamometer output, were configured for a gain of 1000.

Signal connection from the dynamometer to the SCXI-1121 conditioning module, together with strain gauge excitation, was provided via an SCXI-1320 terminal block and a low-noise shielded cable selected to withstand the adverse environment of the explosion chamber.

The output from the infrared thermometer system was also connected to the SCXI-1121 signal conditioning module via the SCXI-1320 terminal block and a shielded cable. However, no further signal conditioning was applied to this output by the SCXI system.

The analogue signals from the SCXI system were connected in parallel mode via a 50-conductor ribbon cable to the NB-MIO-16XL-42 input/output board. The latter is a multifunction analogue, digital and timing input/output board. It includes a 16-bit analogue to digital converter, 16 multiplexed inputs, two 12-bit digital to analogue converters, 8 digital input/output lines and three 16-bit counters/timers.

A further gain of 10 was applied at the input/output board to channel 0, the output from the dynamometer which corresponds to the applied axial force. No further gain was applied to channels 1,2 and 3 which correspond to frictional force, transverse force and temperature respectively.

During analogue to digital conversion, each of channels 0 to 3 was scanned at a rate of 1992 samples per channel per second. This is the fastest available scanning rate (using interrupts) that is an exact multiple of the video camera rate of 24 frames per second.

In order to synchronise the video data with the force and temperature data, an LED mounted on the explosion chamber within the frame of the video camera was illuminated immediately data acquisition commenced. One of the digital input/output lines was dedicated to powering this LED, broken out of the main 50-conductor ribbon cable via a National Instruments SC-2053 cable adaptor board.

3.4.2 *Software*

Software used for data acquisition and manipulation was based on the National Instruments LabVIEW version 3.0.1 running under Macintosh System Software version Z1-7.5.

The LabVIEW software is based on the concept of the virtual instrument, or VI, a software emulation of test equipment that creates, analyses, and displays data much as physical instruments do. It facilitates data capture and analysis without requiring access to dedicated test equipment. It utilises a graphical programming language in which the manipulation of objects replaces the more familiar writing of code. It is used to create applications for data acquisition and management, signal and transient analysis, and process control.

A LabVIEW data acquisition and control VI was created to acquire up to four channels of force and temperature data from the dynamometer and infrared thermometer system and to control the indicator LED which provides the timing synchronisation signal for the video camera.

Input to the VI defined the following parameters. Default values, which may be varied by the user, are given in parentheses.

a. The number of the NuBus slot in which the NB-MIO-16XL-42 input/output board is located. (4)

b. The list of channels from which data is to be acquired. (0-3)

c. The range and polarity of the input/output board. (20 volts, bipolar)

d. The input/output board gain for each of the channels specified in (b). (10, 1, 1, 1)

e. The data acquisition trigger level for channel 1. (minus 22650)

f. The scan rate at which data is to be acquired and written to file, i.e. the number of samples per second per channel of all the listed channels. (1992)

g. The maximum number of scans to read and write to file. (1,000,000)

h. The minimum number of scans to read and write to file from the acquisition buffer at each loop iteration. (1992)

i. The size of the acquisition buffer. (500,000)

j. The inter channel delay, i.e. the interval between sampling each channel in a scan. (hardware default)

The VI set up for the project performs the following functions:

a. Creates an output file and prompts the user for a name.

b. In parallel with (a), configures digital port B on the input/output board for output and sets the output lines from the port to 'low'. (One line from port B is connected to the video synchronisation LED.)

c. Monitors channel 1 (corresponding to the frictional component of force) on the input/output board and compares it with the user-defined trigger level.

d. When the channel 1 output level exceeds the trigger level, sets the output lines from port B to 'high'. (This causes the LED to become illuminated.)

e. In parallel with (d), configures and starts the data acquisition.

f. Writes a stream of signed 16-bit integer data from the analogue to digital converter to the output file until the preset maximum number of scans has been acquired or the stop button is pressed (or until an error occurs - error handling is explicitly provided).

g. Clears the data acquisition and closes the output file.

h. In parallel with (g), sets digital port B to 'low'. (This extinguishes the LED.)

A suite of VIs was also created to manipulate and graphically display the 'raw' data, facilitating the study of the detailed time histories of applied axial force, frictional force and temperature.

An averaging and scaling VI was used to read the signed 16-bit integer data written to file by the data acquisition and control VI described above. It first averages the data over a user-selected number of scans. (The default value is the number of scans which occur within the frame interval of the video camera.) It then scales the data using dynamometer calibration information entered by the user (see below). Finally, it writes the averaged and scaled data to file as a string of single-precision floating-point numbers.

A display VI was used to read the single-precision floating-point data written to file by the averaging and scaling VI and to plot time histories of dynamometer forces and rock temperature. By default, the time base is equivalent to the frame count of the video camera.

Conversion VIs were used to read either the 'raw' data or the averaged and scaled data and convert them into a form which can be read by spreadsheet programs for further manipulation.

Finally, to facilitate calibration (described below), a VI was created which 'grabs' a one-second sample of signed 16-bit integer output from the A/D converter for each of the channels specified by the user. It then plots the 'raw' data from each channel on a waveform chart together with 'smoothed' data from the corresponding channel in the form of a moving mean. The number of coefficients in the moving mean may be specified by the user but the default coefficient is the number of scans which occur within the 1/24 second frame interval of the video camera, i.e. by default, the force and temperature data is averaged over 1/24 second periods). The VI also calculates the overall mean for each channel.

4 CALIBRATION OF THE INSTRUMENT SUITE

4.1 *Dynamometer*

'Right through' calibration of the dynamometer and of the data acquisition system was undertaken using 'dead weight' loading. Testing was undertaken in two modes, namely vertical, corresponding to the applied axial component of force, and horizontal, corresponding to the frictional component.

A very high degree of correlation ($R^2>0.95$) was found between the applied force and the change in dynamometer output in both modes, and the stability of the relationship was proven by repeated testing over time. However,significant zero drift was detected, particularly in the applied axial component of force. The zero drift was of two types : medium term, ie on a day-today or week-to-week basis; and short term, ie before and after a test run using the dynamometer. See section 3.2 for a discussion of the probable causes of the zero drift.

The effect of zero drift was compensated for by measuring the dynamometer outputs corresponding to zero load immediately before and after each laboratory test and using the mean of the values in subsequent calculations.

The procedure developed for calibrating the dynamometer is as follows:

Channel 0 (vertical force)

- Remove dynamometer from chamber and place on floor of laboratory.
- Turn on SCXI box.
- Wait for at least 4 hours to allow the strain gauge to stabilise at zero load, using the LabVIEW 'grab VI' to record the zero drift during this period.
- When strain gauge has stabilised at zero load, continue to use the 'grab VI' to record mean binary readings for loads in the range 0 to 48 to 0 kg, in 1 to 2 kg steps.
- Check "zero load" reading at least twice during the "up" phase and at the end of the "down" phase.
- Use a spreadsheet with a statistical package to display and record regression statistics for the applied load/binary reading output for the loading-unloading procedure.
- Re-install dynamometer in chamber.

Channel 1 (frictional force)

- Calibration is done with the dynamometer installed in the chamber.
- As with Channel 0, check that the system is stable at zero load.
- Replace the screw-in three-point clamp of the dynamometer with a screw-in bolt and rope device.
- Fit a frame and pulley device to the removable wall of the chamber.
- Pass the rope from the screw-in bolt over the pulley, and check that the rope is both horizontal and pulling along the line of the holes in the bolt.
- Attach the hook and platform device, which is usually used to load the dynamometer during testing, to the loop in the rope from the screw-in bolt and load the dynamometer in the horizontal direction by placing masses on the hook and platform device.
- As for Ch0, use the 'grab' VI to record the results of loading over the range 0 to 20 to 0 kg.
- Display and record regression statistics.
- Remove frame and pulley, and screw-in bolt and rope devices.

4.2 Pyrometer Calibration

The Mikron M77LS Infraducer had been factory calibrated and certified as giving a 4-20 mA output which was proportional to temperature between 700 and 2000 degrees Celsius to an accuracy of ±0.5% when using the 'blackbody' setting (emissivity equal to unity).

The rock wheels were considered to be 'greybody' targets, i.e. exhibiting no changes in emissivity within the two spectral bands used by the Infraducer. Consequently, for the laboratory calibration of the Infraducer plus signal conditioning module, the former was set to 'blackbody' while the 'slope' adjustment of the latter was retained at its default setting (equal to unity, implying zero change in emissivity within the two spectral bands).

The results of the laboratory calibration over a range of temperature from 700 to 1300 degrees Celsius against a thermocouple using a Hilldav Industries electric kiln model 1.3BL indicated good agreement.

4.3 Proving of Instrumentation

Prior to the routine testing of samples commencing, numerous 'proving' runs were undertaken to check the functioning of the instrumentation.

The material used was a quartzose sandstone with an IGCAT of 3.

The following proving program was undertaken:

- Test runs at 500 rpm and an external load of 4.327 kg to check the triggering of the acquisition program and to confirm that all channels were recording simultaneously.

- Test runs at 500 rpm to compare the response to the 'normal' external load of 4.327 kg with the response to hand loading.

- A combination of test runs at 500 rpm and 'normal' loading, and static (ie no rotation and no load) runs with data acquisition over a period of 8 minutes, to demonstrate the effect of zero drift. The static runs were conducted with and without sliders and mounting fittings on the dynamometer, to investigate the effect of the heat generation during dynamic tests.

- Test runs at different rotational speeds and external loads.

- The checking of the responses of the video camera and pyrometer in different viewing positions. Two basic positions were adopted:

  for tests with chamber filled with ~7.5% methane/ air mixture: video camera viewing parallel to axis of rotation and pyrometer viewing from vicinity of corner of plastic 'blow-out' wall at approximately 45° to axis of rotation;

  for tests with no methane in chamber : video camera and pyrometer viewing from vicinity of safety grill in 'blow-out' wall, at 90° to axis of rotation.

An example of the output of the instrumentation during proving runs is shown in Figure 4.1.

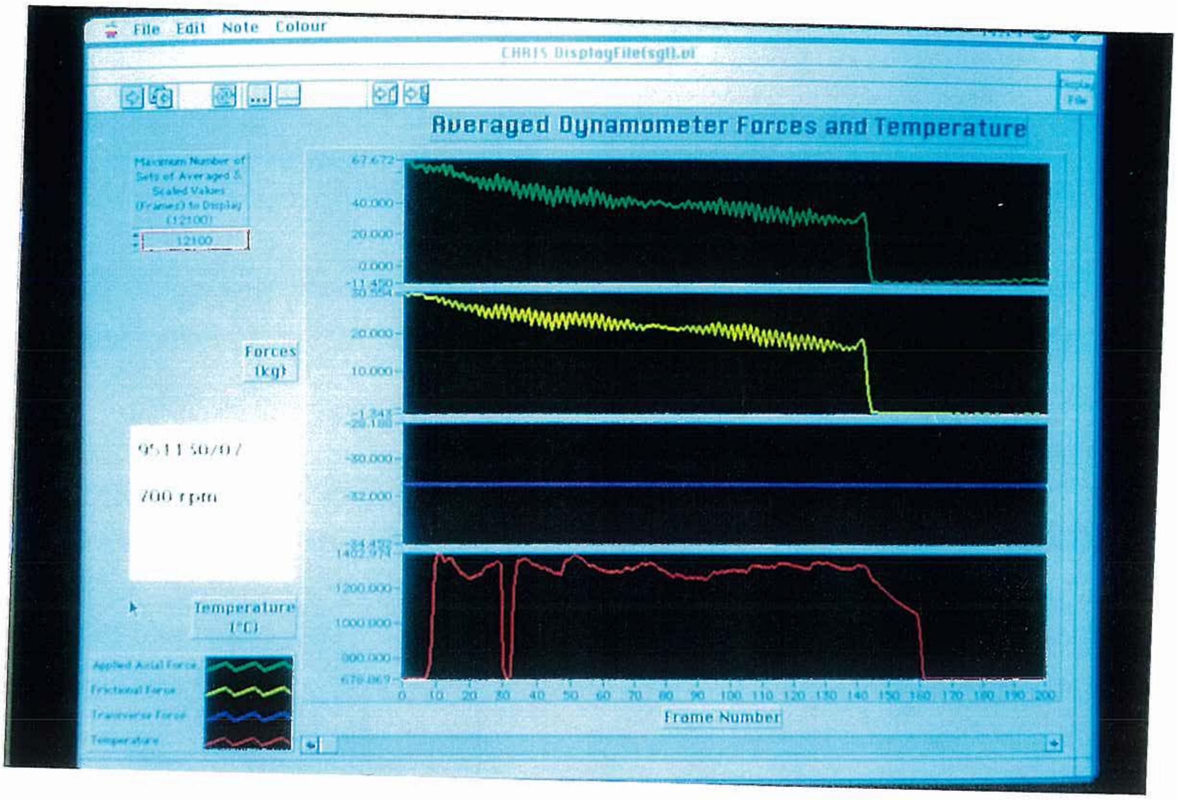


Figure 4.1: Photograph of Macintosh Quadra computer screen showing normal force (top panel), shear (frictional) force (second from top), lateral (transverse) force (third from top, not recorded due to strain guage failure) and temperature (bottom panel).

5 SAMPLING AND ROCK CHARACTERISATION

5.1 Sample Collection

The previous frictional ignition project, carried out with support from the NERDDP (Ward et al., 1990, 1991a,b) tested a fairly comprehensive range of rock samples from New South Wales and Queensland mines. Additional samples were gathered for the present project, partly to extend the overall database of materials and their frictional ignition properties and partly to provide fresher material to continue the testing program.

Because no single sample can represent the full range of materials likely to be encountered in any one colliery holding, a number of additional samples were collected for present investigation from mines that had been sampled in the previous (1987-1990) project (e.g. Appin, South Bulli, Moura, German Creek). In most cases the samples taken represented different lithologies to those which had been tested before. Opportunity was also taken, however, to collect samples from a number of mines which had not been sampled previously (e.g. South Bulga, Newlands, Gordonstone), and also of a number of different rock types such as pyritic mudstone and siliceous coal, which had not previously been investigated in the UNSW test rig.

Opportunity was also taken to include in the sample suite a number of rocks from colliery areas in Germany and Japan. These provided an insight into the applicability of the study to mines in other countries, and also a basis for cross-reference of the UNSW project to incendivity work being carried out in other national centres.

A list of the new samples collected for the present project is given in Table 5.1

5.2 Rock Characterisation

The analysis and testing program for the sample suite is summarised in Table 5.2. The details for each test category are:

- *XRD* : x-ray diffraction analysis of a powder sample, carried out at the University of New South Wales Department of Applied Geology using a Philips PW3710 based 'X'pert' diffractometer. The resulting diffractograms were interpreted by reference to the JCPDS Powder Diffraction File and a qualitative assessment of the relative abundance of the components made.

- *XRF* : concentration of major oxides and loss-on-ignition at 1050°C, using the Department of Applied Geology's fully automated Siemans SRS 300 XRF with Spectra-AT software. With some samples the acid-soluble component was determined by solution in hydrochloric acid.

- *Petrology* : preparation of thin sections at the Department of Applied Geology; optical microscopy and modal analysis based on point counting (400 points per slide); normative mineralogical analysis using the computer program SEDNORM

(Cohen and Ward, 1991) to interpret the chemical analysis from XRF in the light of the XRD results.

- *IGCAT* : ignition category (Ward et al, 1990) by testing cylindrical wheels of approximately 150 mm diameter and sliders of the same material in the University of New South Wales School of Mines frictional ignition unit. In some cases, sliders if different composition were tested against a 'standard' rock wheel.

- *Dyn* : use of a pick-force dynamometer, designed and constructed at the School of Mines during the course of the present project, to measure the normal and lateral forces applying during the testing of rock wheels and sliders in the School of Mines frictional ignition unit. In the case of some samples which had been tested for IGCAT before the pick-force dynamometer was calibrated and commissioned, there was insufficient sample remaining to allow dynamometer testing.

- *Temp* : use of a non-contact pyrometer to measure temperature at the active contact point between rock wheel and slider during testing in the School of Mines frictional ignition unit.

Table 5.1 Sample locations and rock types for the 1993/95 project

Source	*Sample no.*	*Material*	*Location*
Appin Colliery (NSW)	Appin 3	Sandstone, lithic	Not identified
CSIRO Div of Exp & Mining	JP-S1 JP-S2 JP-S4	Sandstone, lithic Wood, silicified Sandstone, lithic	Japanese coal measure rocks, supplied as part of a collaborative research project with the Mining Research Centre, Japan.
Clutha Minerals	CL1	Sandstone	Brimdale Colliery
DMT (Germany)	15899 16253 76231	Sandstone S/s, calcareous Sandstone Sandstone S/s, calcareous	German coal measure rocks, supplied for comparative testing of frictional ignition characteristics.
German Creek Colliery (Qld)	9501 GC	Sandstone, lithic	Southern coll., vicinity 25 c/t, 701 t/gate ~0.25m above roof of German Ck seam.
Gordonstone Colliery (Qld)	Gord 2	Sandstone	Underground, roof of German Ck seam
Moura Colliery (Qld)	Moura 2	Sandstone	Open-cut, C/B seam
Newlands Colliery (Qld)	9502 NL	Sandstone, lithic	Open cut, above roof of Upper Newlands seam.
Oaky Creek Colliery (Qld)	Oaky Creek 1 Oaky Creek 2	Sandstone, lithic Sandstone, lithic	Not identified Not identified
South Bulga Colliery (NSW)	SB 10	Coal, silicified	South Bulga underground, Whybrow seam
South Bulli Colliery (NSW)	Sth Bulli 2	Mudstone	Not identified

Table 5.2 testing program for samples from 1993/95 project

Sample no.	*XRD*	*XRF*	*Petrology*	*IGCAT*	*Dyn.*	*Temp.*
Appin 3	√	√		√	√	?
JP-S1	√	√	pc	√	nt	nt
JP-S2	√	√	pc	√	nt	nt
JP-S4	√	√	pc	√	nt	nt
CL1	√	√	√	√	√	√
15899	√	√	√	√	√	√
16253	√	√	√	√	√	√
76229	√	√	√	√	√	√
76230	√	√	√	√	√	√
76231	√	√	√	√	√	?
9501 GC	√	√	√			
Gord 2	√	√	√	√	√	√
Moura 2	√	√	√	√	√	√
9502 NL	√	√	√	√	√	√
Oaky Ck 1	√	√	√			
Oaky Ck 2	√	√	√			
SB 10	√	√	nd	√	nt	nt
Sth Bulli 2	√	√		nd	√	nd

√ : analysis and/or testing
nd: not determined
nt: not tested
pc: point count only

6 RESULTS

6.1 Petrographic and Mineralogical Investigations

As with the previous study, the rock materials tested for the present project were characterised by a combination of mineralogical, geochemical and petrographic techniques. These included:

1) Thin-section petrology, with observational data on gross textural attributes (e.g. grain size, packing and cementation) and quantitative data through point counting on the relative proportions of key mineralogical components;

2) X-ray diffraction (XRD) analysis, with quantitative data on the relative abundance of key minerals using supplementary XRD investigations of samples to which a known proportion of mineral spike had been added (cf. Ward, 1977);

3) Chemical analysis using X-ray fluorescence (XRF) techniques, elemental analysis (e.g. for carbon content) and supporting wet-chemical methods;

4) Normative assessment of a "theoretical" mineralogy, based on chemical analysis data in the light of microscopy and XRD results, using a computer program, SEDNORM, developed specifically for sedimentary rock materials (Cohen and Ward, 1991).

Petrographic and mineralogical data on the new samples studied for the project are given in Appendices A1.1, A1.2 and A1.3. Further information on the siliceous coal from South Bulga Colliery, a rock type which has not been previously been included in ignition test programs, is given in Appendix C1.1.

6.2 Basic Incendivity Testing

The rock-on-rock frictional incendivity characteristics of the new samples collected for the project were tested using the methodology developed for the previous NERDDP-funded research program (Ward et al., 1990, 1991a,b). With some exceptions (see below) this involved preparation of a cylindrical rock wheel from the sample, approximately 150 mm in diameter, and rotating that wheel in a methane atmosphere against a slider prepared from another portion of the same rock sample (Figure 3.5). The ease or otherwise of igniting the methane under these conditions at three different rotational speeds (300, 500 and 700 RPM) was then used to assign an ignition category (IGCAT value, see Figure 2.1) from 1 (lowest) to 5 (highest) to the rock sample in question. The results of this testing are given in Appendix A1.4.

Statistical analysis was performed on these data, integrating them where necessary with the data of the previous project (Ward et al., 1990) to establish further the correlations between ignition category and other geological parameters. The results of this analysis are discussed separately in Section 6.3.

Some materials, particularly the siliceous coal sampled from South Bulga colliery, were too brittle or too fractured to allow a 150 mm wheel to be prepared for the testing process. It was also recognised that the need to prepare a wheel of that size required a relatively large sample to be taken from the mine site in question. The collection of large samples, especially large samples free of mechanical discontinuities, is not always possible, and this limits the usefulness of the IGCAT test procedure.

A series of tests was therefore also carried out as part of the project to investigate relative incendivity by placing small sliders of individual rock samples against a rotating wheel of a different rock material (Coates, 1995). If successful, and if an appropriate reference wheel could be identified, this had the potential to widen the applicability of the IGCAT test by allowing materials, such as rocks encountered in exploration drill cores, to be evaluated even where only a small-sized sample was available. The results of these studies discussed separately in Section 6.5.

6.3 Statistical Analysis

Statistical assessment and testing of the data derived from petrographic and geochemical analysis and basic ignition testing was undertaken, to re-evaluate previous data patterns (Ward et al, 1990) and to further establish approaches to predicting the ignition category (IGCAT) on the basis of other chemical and mineralogical variables. Data analysis was performed using the SYSTAT software package.

6.3.1 Statistical Procedures

The general statistical procedures adopted are described by Davis (1986). Although the data set is expanded from the previous project, the limited number of data points precluded rigorous application of parametric procedure, including data transformations to normal distributions. The three procedures applied to the data, after removal of gross outliers, were:

a) determination of correlations between IGCAT and selected variables

b) generation of a series of multi-variate regression equations. These equations provided a prediction of the IGCAT value and the predicted value was plotted against the original IGCAT value.

c) plotting of selected combinations of variable on ternary diagrams and fitting boundaries which best separated the IGCAT groupings.

The procedures for outlier rejection are described in Ward et al (1990), and include data modelling using probability plots.

6.3.2 Bivariate Correlations

XY-plots of Ignition Category with other Rock Parameters

XY-plots of IGCAT versus selected variables or variable combinations are presented in Figures 6.1 and 6.2. The correlation coefficients are listed in Table 6.1 and divided into significant, marginal and non-significant groupings. The data were not modified in these plots nor were outliers excluded. The results for groups of linked variables are discussed below, however, there is no significant change, by addition of the 16 samples analysed in this project , to the patterns established in the previous project (Ward et al, 1990).

Silica and quartz

Positive correlations exist between IGCAT and the normative quartz content, and between IGCAT and chemically determined SiO_2. The carbonates do not fall within the main data trend (0% SiO_2 and IGCAT of 1). In both cases there is a large spread of data at intermediate IGCAT values; at IGCAT 3.5 for example, normative quartz ranges from 25 to 82% and SiO_2 from 55 to 90% (this range is extended by the new data generated in this project). Similarly, at a normative quartz content of 50% (a critical value on the NCB classification), IGCAT varies from 2 to 4.5.

Systematic trends were again more pronounced in the upper boundaries to the data spread than in direct correlations. In the case of Figure 6.2, there is a distinct relationship between maximum quartz content and IGCAT;

$$\text{IGCAT} = \frac{\text{Maximum SiO}_2 - 40}{12}$$

There were strong correlations between total silica (SiO_2) determined by chemical analysis and "theoretical" quartz determined by normative calculation, but weaker correlations with quartz percentage determined by point count and XRD methods. In each case, the spread of values is seen to increase with decreasing silica, a factor related to both variations in mineralogy and mis-classification of some quartz in the finer grained rocks.

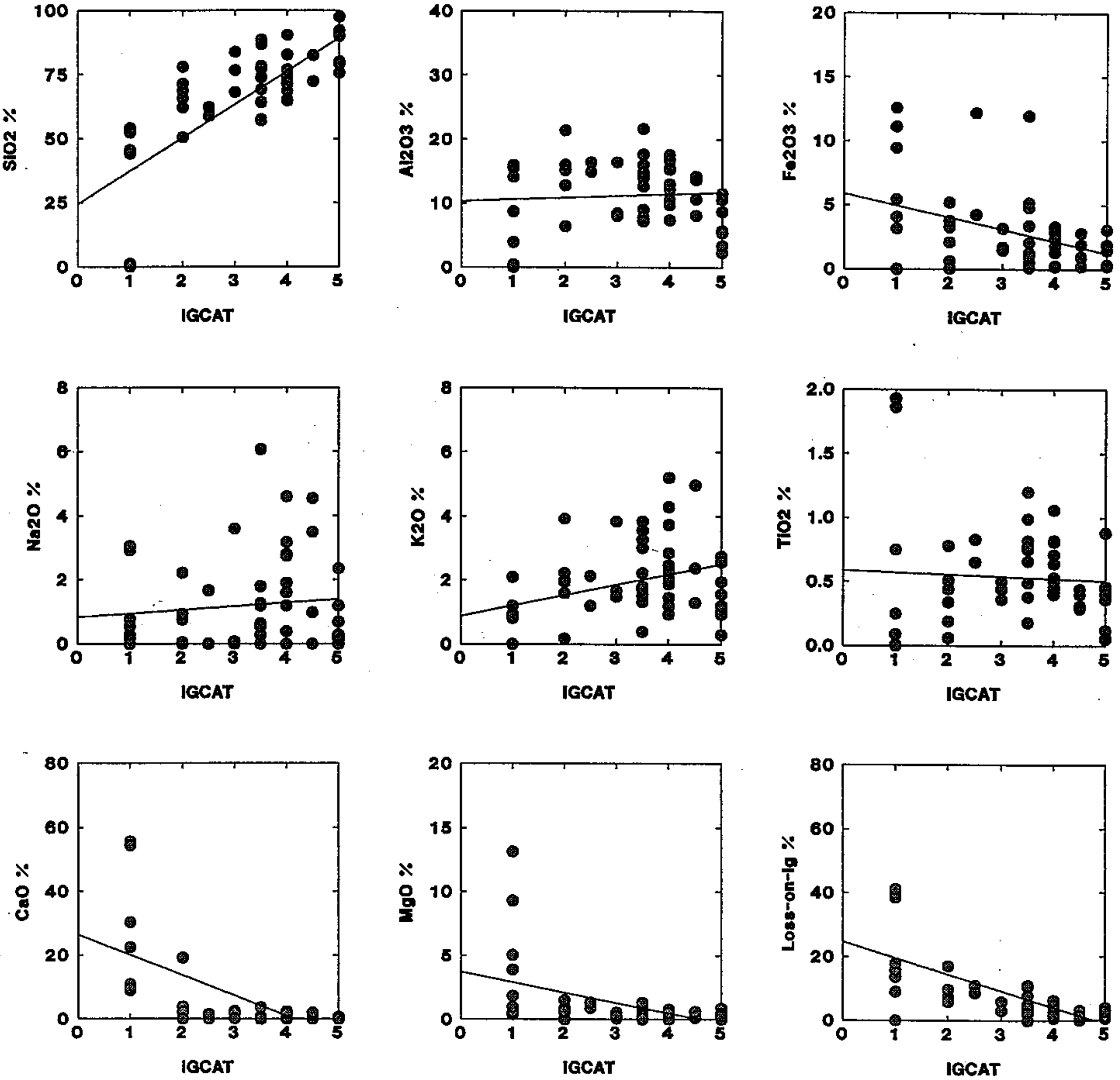


Figure 6.1: Plots of IGCAT against XRF major oxide data.

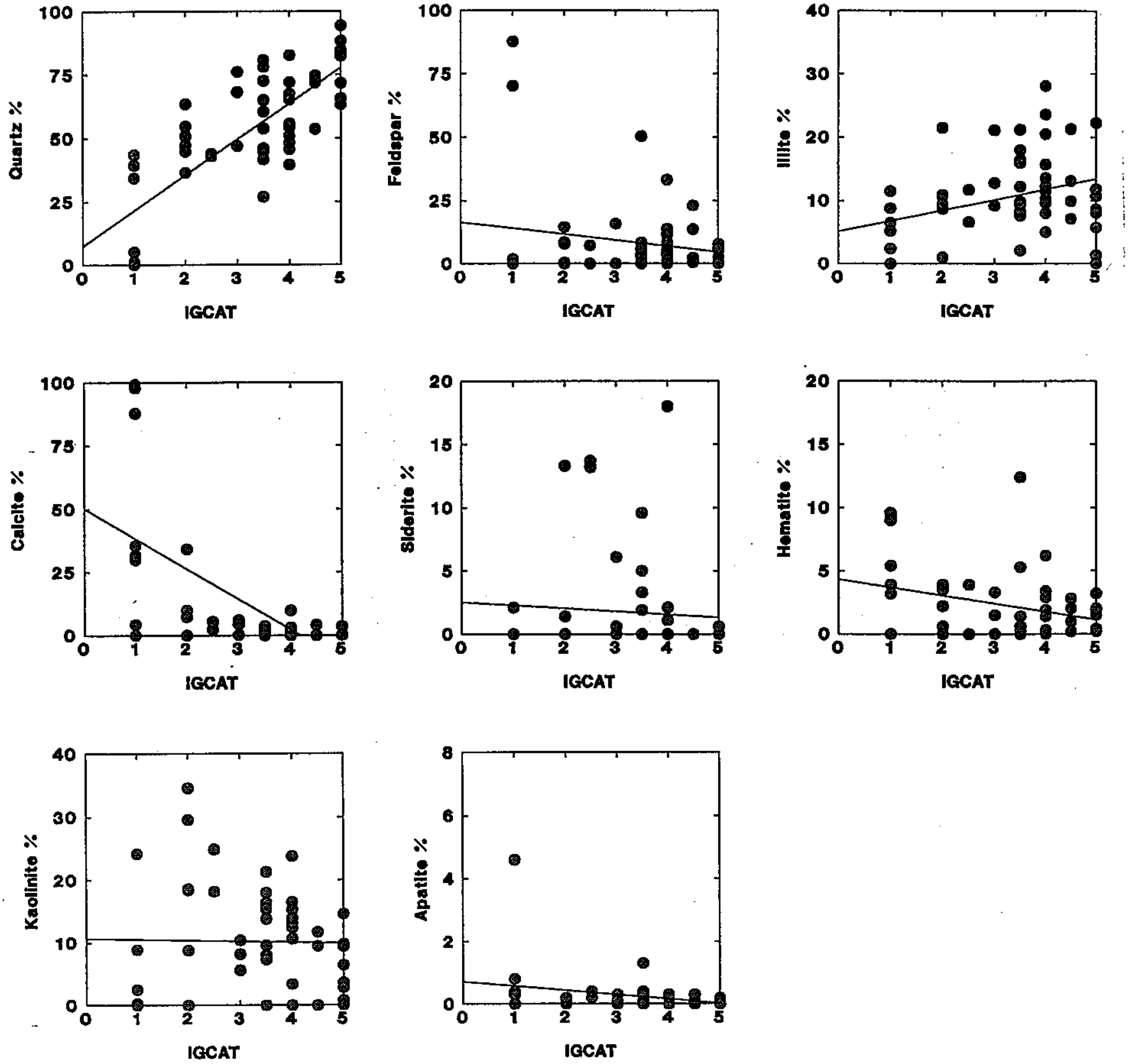


Figure 6.2: Plots of IGCAT against SEDNORM mineralogy.

Alumina, feldspar and clay

A weak negative correlation was noted between IGCAT and Al_2O_3, but no direct correlation was observed individually between IGCAT and feldspar. As in the case of silica, there is a well developed limit to the maximum amount of clay + mica for a given IGCAT value (although it is a negative trend in this case). There is also a moderately strong negative correlation between IGCAT and total water content or water loss at 1050°C.

Carbonate minerals

A very strong negative correlation was observed between IGCAT and both carbonate content and CaO (most of the samples are chemically mature, hence most of the Ca is bound up as calcite).

6.5.3 Non-Parametric Correlation

Spearman rank correlations express the similarity between equivalent rank values for two variables (Davis, p.98). Although there are fewer non-parametric rank correlations than parametric in the data set, similar data pairs were shown to correlate including IGCAT-SiO_2, IGCAT-QRTZ and the set ACID-CO_2-LOI-CTE. Negative correlations were also found between this latter set and the IGCAT value. Al_2O_3 is correlated with ACID implying some dissolution of clays in the analysis or more carbonates in the finer sediments.

6.5.4 Multi-element Correlations and Development of IGCAT Predictors

As in the case of cluster and factor analysis, multiple regression methods seek to summarise and simplify relationships between a series of variables. Multiple regression analysis is an extension of bivariate correlations and in the application here, the objective is to express the key or dependent variable - IGCAT - in terms of linear combinations of other variables, i.e. to identify a relationship in the form:

$$IGCAT = k_0 + k_1V_1 + k_2V_2 + k_3V_3 + ... + \mathfrak{m}$$

where V_1 is a variable, k_1 are co-efficients and $\mathfrak{m}$ is the random error.

The purpose of this statistical application in the present study was to determine whether a reasonably accurate estimate of the ignition category of a sample can be made on the basis of combinations of other data more easily obtained in routine mine operations than actual ignition chamber tests. The utility or efficiency of each multiple regression model is measured by the correlation (R^2) between the actual IGCAT values and the values predicted by the multiple-regression model. The efficiency of the model, in this case where the IGCAT values are ordinal, may be tested by a cross-tabulation of observed versus predicted IGCAT (in this case the regress IGCAT value has been reduced to 0.5 IGCATs intervals).

Table 6.1: Bivariate correlations versus IGCAT

Variable	Correlation Coefficient	Signif	Variable Type
SiO_2	0.762	high	XRF
K_2O	0.347	high	XRF
Fe_2O_3	-0.390	high	XRF
MgO	-0.488	high	XRF
CaO	-0.631	high	XRF
LOI	-0.685	high	XRF
QM	0.560	high	Point Counting
CTE	-0.652	high	Point Counting
QRTZ	0.778	high	SEDNORM
ILLI	0.329	high	SEDNORM
CALC	-0.622	high	SEDNORM
MnO	-0.250	marginal	XRF
QP	0.308	marginal	Point Counting
HAEM	-0.309	marginal	SEDNORM
Na_2O	0.106	none	XRF
Al_2O_3	0.069	none	XRF
TiO_2	-0.057	none	XRF
SO_3	-0.190	none	XRF
MIC	0.168	none	Point Counting
RF	0.053	none	Point Counting
MAT	0.011	none	Point Counting
XCL	-0.003	none	Point Counting
OP	-0.080	none	Point Counting
FEL	-0.113	none	Point Counting
KAOL	-0.023	none	SEDNORM
SIDE	-0.079	none	SEDNORM
FELD	-0.190	none	SEDNORM

A series of models was tested with variables selected on the basis of their previously established correlations with IGCAT (from the correlation tables, XY-plots, cluster and factor analysis) or by origin (XRF data, SEDNORM normative mineralogy). Five models have been selected and the results are included in Table 6.2, with plots of observed IGCAT versus predicted IGCAT in Figure 6.3.

Table 6.2: Selected multi-variate predictor (regression) models for IGCAT, analysis of variance on models and two-way contingency table of Original vs Predicted IGCAT values.

Model 1. Variables selected after step-wise regression (F-to-enter = 2)

Dependent Variable:	IGCAT
N:	53
R-squared:	0.682

Variable	Coefficient
Constant	0.460
QRTZ	0.042
K_2O	0.298

Analysis of Variance

Source	SS	Df	MS	F-Ratio	Risk (p)
Regression	64.019	2	32.010	53.722	0.000
Residual	29.792	50	0.596		

Table of IGCAT Values (Rows) by Predicted IGCAT Values (Columns)

FREQUENCIES

	1	**2**	**2.5**	**3**	**3.5**	**4**	**4.5**	**5**
1	6	0	2	1	0	0	0	0
2	0	0	0	1	4	1	0	0
2.5	0	0	0	2	0	0	0	0
3	0	0	0	0	0	2	1	0
3.5	0	0	0	2	2	5	1	0
4	0	0	0	0	4	5	2	0
4.5	0	0	0	0	0	1	3	0
5	0	0	0	0	0	3	3	2

% correct classification = 35
% classification within 0.5 IGCAT units = 65

Model 2. Selection of all variables with significant correlation coefficient with IGCAT

Dependent Variable:	IGCAT
N:	53
R-squared:	0.719

Variable	Coefficient
Constant	-2.467
QRTZ	0.075
K_2O	0.438
Fe_2O_3	0.046
FELD	0.036
MgO	-0.052
KAOL	0.008
CALC	0.025
SIDE	0.011
LOI	0.017

Analysis of Variance

Source	SS	Df	MS	F-Ratio	Risk (p)
Regression	67.412	9	7.490	12.200	0.000
Residual	26.399	43	0.614		

FREQUENCIES

	1	**2**	**2.5**	**3**	**3.5**	**4**	**4.5**	**5**
1	4	3	1	1	0	0	0	0
2	0	0	1	2	3	0	0	0
2.5	0	0	1	1	0	0	0	0
3	0	0	0	0	0	2	1	0
3.5	0	0	0	2	3	4	1	0
4	0	0	0	1	5	2	3	0
4.5	0	0	0	0	0	0	2	2
5	0	0	0	0	0	3	2	3

% correct classification = 28
% classification within 0.5 IGCAT units = 70

Model 3. XRF data

Dependent Variable:	IGCAT
N:	53
R-squared:	0.753

Variable	Coefficient
Constant	15.161
Al_2O_3	-0.277
CaO	-0.188
Fe_2O_3	-0.268
K_2O	0.071
LOI	-0.099
MgO	-0.238
MnO	5.689
Na_2O	0.171
SiO_2	-0.099
SO_3	0.020
TiO_2	0.185

Analysis of Variance

Source	SS	Df	MS	F-Ratio	Risk (p)
Regression	70.606	11	6.419	11.341	0.000
Residual	23.206	41	0.566		

Table of IGCAT Values (Rows) by Predicted IGCAT Values (Columns)

FREQUENCIES

	1	**2**	**2.5**	**3**	**3.5**	**4**	**4.5**	**5**
1	5	1	2	1	0	0	0	0
2	0	1	0	3	1	1	0	0
2.5	0	0	1	1	0	0	0	0
3	0	0	0	0	0	2	1	0
3.5	0	0	0	1	3	4	2	0
4	0	0	0	1	2	6	2	0
4.5	0	0	0	0	0	1	2	1
5	0	0	0	0	0	1	2	5

% correct classification = 45
% classification within 0.5 IGCAT units = 72

Model 4. SEDNORM mineralogy

Dependent Variable:	IGCAT
N:	53
R-squared:	0.734

Variable	Coefficient
Constant	-3.016
APAT	-0.333
CALC	0.036
FELD	0.043
HEAM	0.073
ILLI	0.084
KAOL	0.013
QRTZ	0.081
SIDE	0.038

Analysis of Variance

Source	SS	Df	MS	F-Ratio	Risk (p)
Regression	68.883	8	8.610	15.198	0.000
Residual	24.928	44	0.567		

Table of IGCAT Values (Rows) by Predicted IGCAT Values (Columns)

FREQUENCIES

	1	**2**	**2.5**	**3**	**3.5**	**4**	**4.5**	**5**
1	4	4	0	1	0	0	0	0
2	0	0	1	3	2	0	0	0
2.5	0	0	1	1	0	0	0	0
3	0	0	0	0	0	2	1	0
3.5	0	0	0	3	3	3	1	0
4	0	0	0	0	4	4	3	0
4.5	0	0	0	0	0	1	3	0
5	0	0	0	0	0	3	1	4

% correct classification = 36

% classification within 0.5 IGCAT units = 70

Model 5. Composite variables

Carbon = Acid leachable carbonate
C_M = Clays + micas
QRF = Quartz + rock fragments + feldspar

Dependent Variable:	IGCAT
N:	53
R-squared:	0.710

Variable	Coefficient
Constant	0.167
Carbon	0.027
C_M	0.014
QRF	0.022
LOI	-0.056
QRTZ	0.030

Analysis of Variance

Source	SS	Df	MS	F-Ratio	Risk (p)
Regression	66.580	5	13.316	22.983	0.000
Residual	27.231	47	0.579		

Table of IGCAT Values (Rows) by Predicted IGCAT Values (Columns)

FREQUENCIES

	1	**2**	**2.5**	**3**	**3.5**	**4**	**4.5**	**5**
1	5	1	2	0	1	0	0	0
2	0	0	3	0	3	0	0	0
2.5	0	0	0	1	1	0	0	0
3	0	0	0	0	1	1	1	0
3.5	0	0	1	1	2	4	2	0
4	0	0	0	0	3	6	2	0
4.5	0	0	0	0	0	1	3	0
5	0	0	0	0	0	1	4	3

% correct classification = 36
% classification within 0.5 IGCAT units = 76

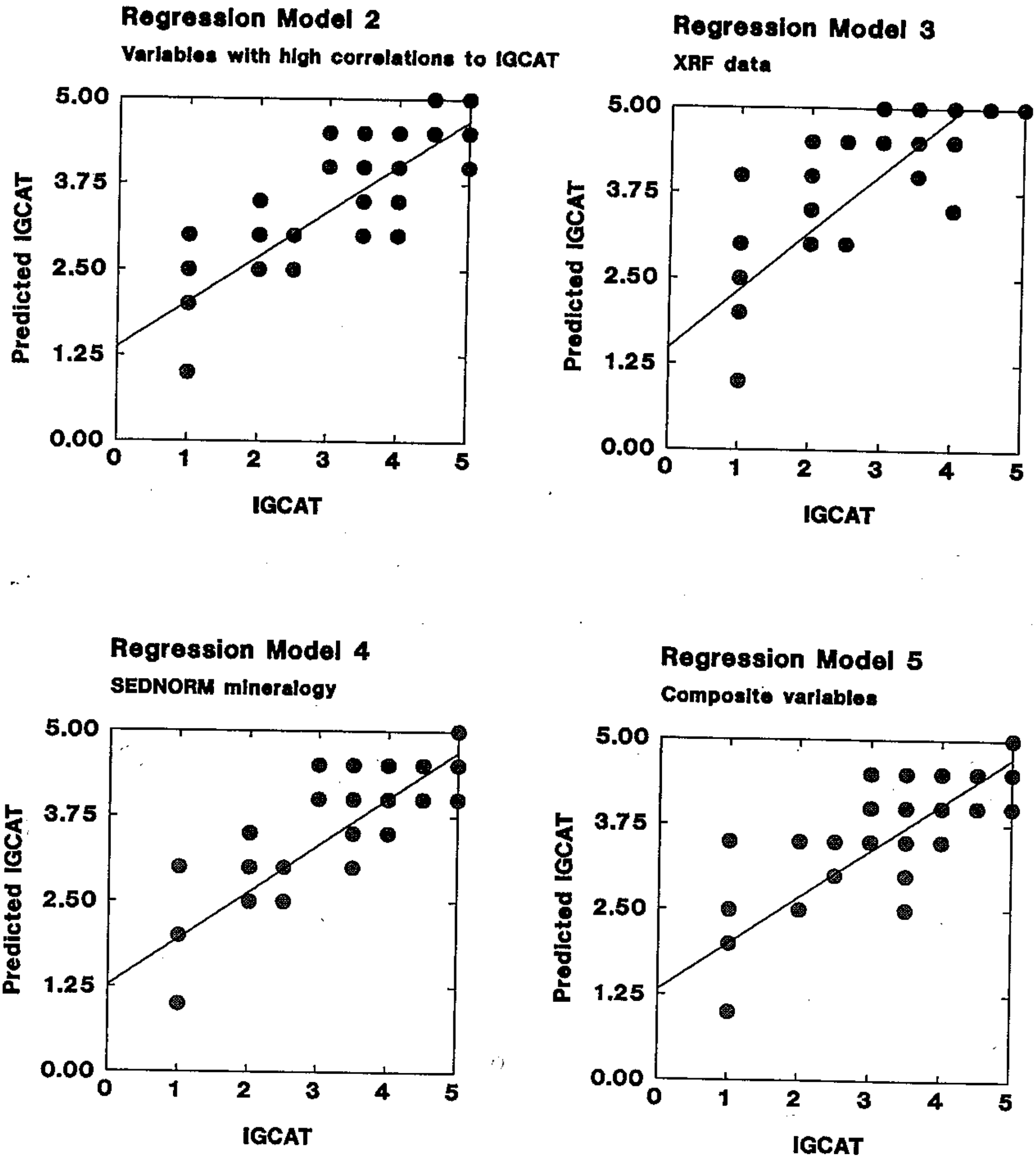


Figure 6.3: Comparison of Original vs Predicted IGCAT values for model 2 (inclusion of all variables with high correlations to IGCAT); model 3 (XRF-data); model 4 (SEDNORM data) and model 5 (combination variables used in ternary plots)

6.5.5 Ternary Diagrams

As well as the various statistical procedures described, ternary (triangular) diagrams were used to investigate the relationships between IGCAT and other geological parameters. The diagrams used for the present project are more accurately described as pseudo-ternary diagrams, since the parameters plotted were not necessarily selected from the one data group (e.g., XRF major oxides). The three parameters or variables chosen (V1, V2 and V3) were therefore not constrained by the usual relationships among components plotted on such diagrams, namely:

V1 + V2 + V3 **O** 100 % and 0% **O** V1,V2,V3 **O** 100%

Hence, a sample with variables A, B and C of 10%, 5% and 18% will plot in the same position as a sample with values of 20%, 10% and 36%, even though the total sum A+B+C is clearly different in each case.

Each of the variables plotted therefore was first scaled between 0 and 100, a process which effectively standardised the data. This allowed unrelated parameters such as SiO_2.

The clearest spread between IGCATs was provided by the following two ternary systems:

Model	*Co-ordinate end-member* *A*	*B*	*C*
1	Quartz+Feldpar[1]	Clay+Mica[1]	Carbonate[1]
2	XRD-quartz	Carbonate[1]	LOI

[1] point count data from detailed petrological analysis

A strong differentiation of IGCAT is apparent in Figure 6.4, along both the A-B and A-C axes, with an increase in quartz+feldspar or a decrease in carbonate or clay+mica contributing to an increased IGCAT value. Comparing the A-B and A-C axes, it is apparent that an increase in the relative carbonate content reduces the IGCAT value to a greater extent than an equivalent increase in the relative clay+mica content. As the loss-on-ignition (LOI) is affected by variations in clay, mica and total carbonate, and given that feldspar contents in the samples did not correlate with IGCAT, the quartz percentage estimated by X-ray diffraction was substituted for quartz+feldspar and LOI substituted for clay+mica. Again there was a well defined spread of values (apart from the mixing of IGCAT values greater than 4). LOI is also demonstrated to have a greater affect on IGCAT than total carbonate for a given quartz content.

In the other ternary plots, the parameters selected failed to provide adequate grouping of IGCAT values and separation of those groups.

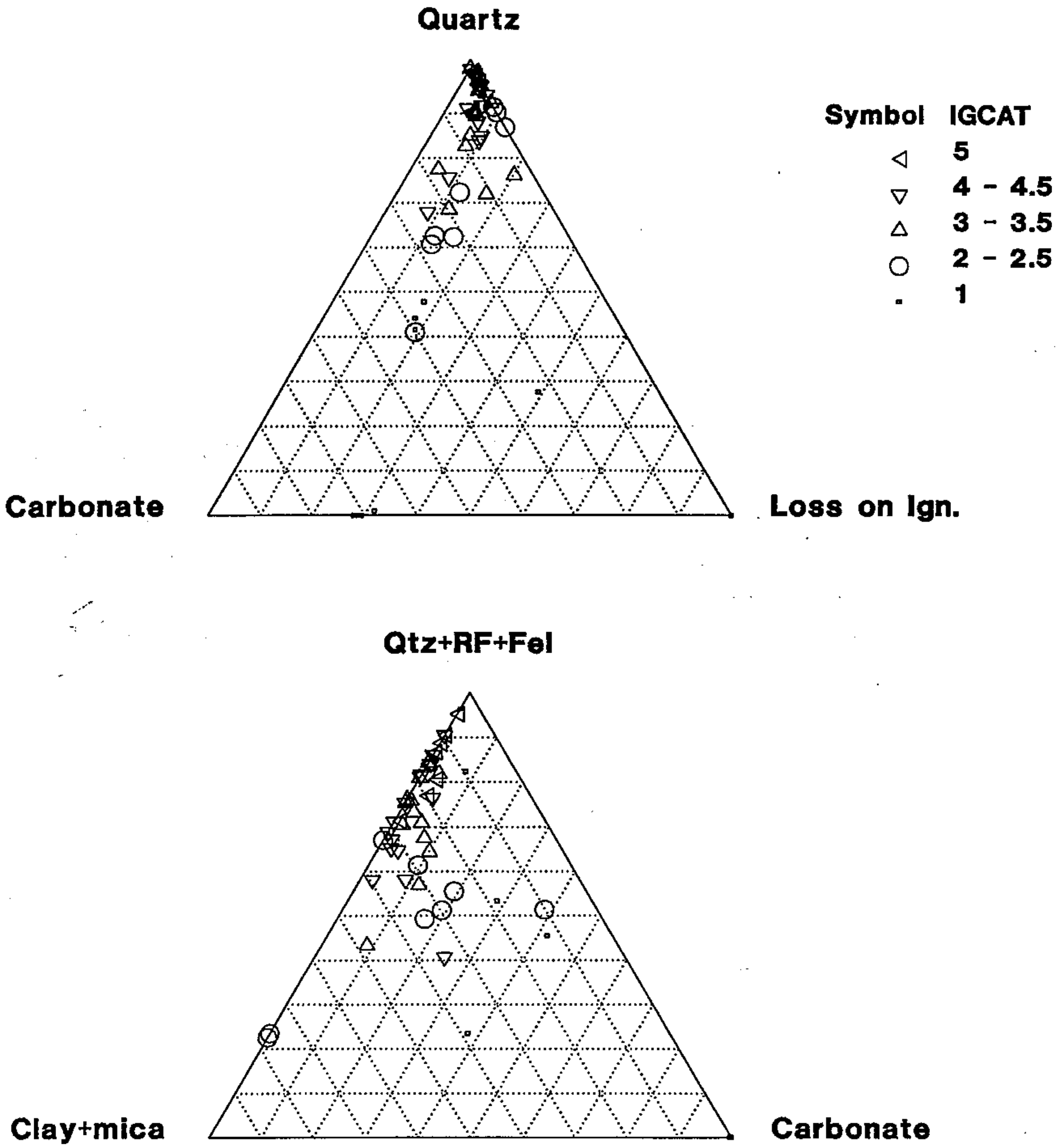


Figure 6.4: Ternary plots for selected groups of variables.

6.4 Pick-on-rock Tests

As mentioned above, a limited amount of incendivity testing using metal miner picks on different rock wheels (pick-on-rock rather than rock-on-rock testing) was carried out as part of the 1987-1990 investigation. Working in collaboration with CSIRO Division of Exploration and Mining and the Mining Research Institute of Japan, a follow-up series of tests was carried out, as part of the present project, to evaluate further the relative incendivity of different coal mine rocks in pick-on-rock rather than rock-on-rock situations.

The samples tested in this study had IGCAT values, determined from rock-on-rock testing, of between 2 and 3. One sample (JP-S4) was tested in both a dry and a wet state. The wheel from this sample was oven-dried for 24 hours at 60°C and weighed. It was then immersed in water for 24 hours, after which it was re-weighed and the absorbed moisture content calculated to be 6.5%. The other samples were tested only in the dry state.

A series of tests was performed on these rocks, using Kameyama type point-attack picks supplied by CSIRO. Special pick holders were constructed for the work, allowing the picks to be held at a critical angle against the rotating rock wheel. Some of the picks tested had been ground separately to simulate wear, and the contact angle with the wheel was arranged to be tangential to the pick at the junction of the tungsten carbide tip and the shank material. The size and arrangement of the pick holder prevented use of the instrumentation system, and hence an empirical approach was used to determine the pick force and feed rate.

Within a few seconds of the initial contact in each case a groove had developed in the rock (Figure 6.5), so that the shoulder of the pick was in constant contact with the rock surface. Fine rock dust filled the ignition chamber, but prior to final obscuration a minor yellow hot spot was observed at the point of contact with the rock.

Examination after the tests generally indicated minimal wear on the tungsten carbide tip of the pick, but significant wear on the shank metal. No ignitions occurred in any of the tests run on these samples (Table 6.3), despite adjustments to the pick angle to maximise the frictional contact. The picks, however, showed evidence of heat discoloration on the shank metal after the tests had been carried out (Figure 6.6).

Ignitions did occur, however, with point-attack picks on higher IGCAT rocks tested in a similar apparatus as part of the 1990 NERDDP investigation.

Figure 6.5: 150 mm diameter wheel prepared from sample JPS-1, showing grooves cut by picks during ignition tests.

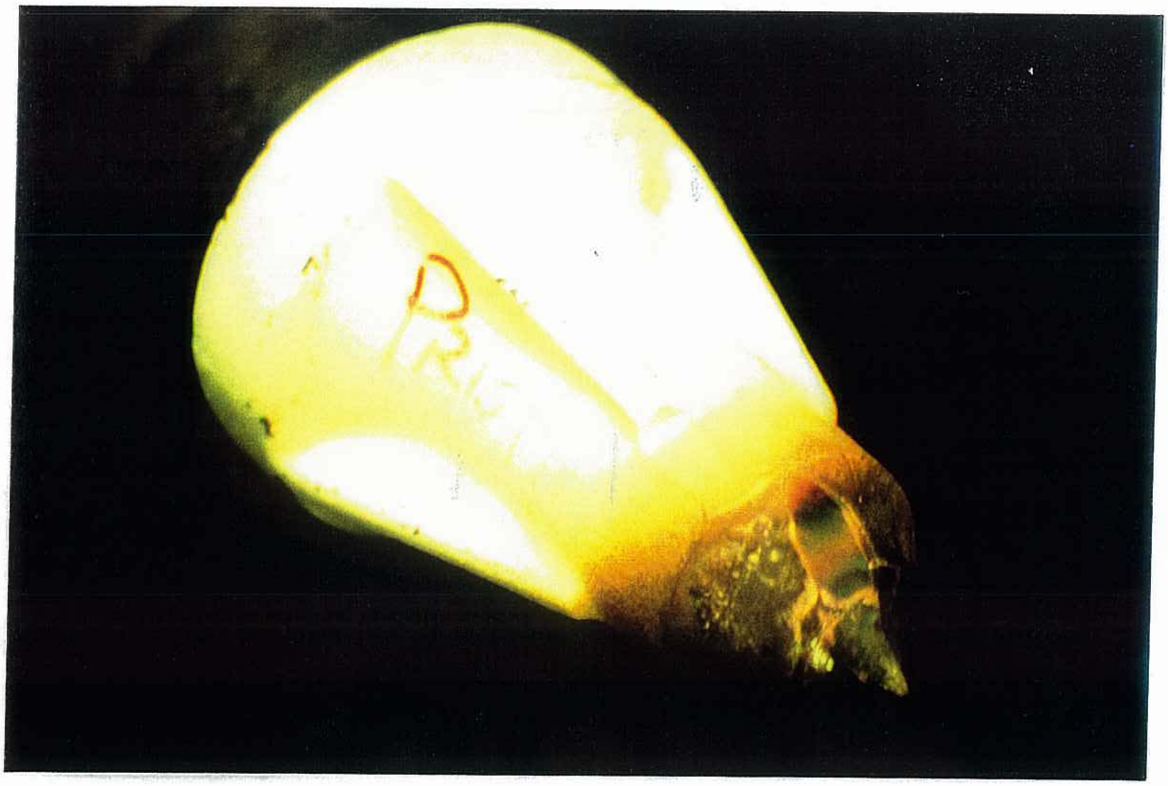


Figure 6.6: Originally pristine pick, showing flattened face and heat alteration after contact with sample JPS-1 during ignition tests.

Table 6.3: Results of cutter pick tests.

JP S1 DRY

RPM	CH_4%	IGNITION	TIME (s)	PICK	COMMENTS
500	7.0	N	240	P	pick cut rock deeply to shank level
500	7.0	N	240	P	some chipping of sample at edge
500	7.0	N	240	P	
500	7.2	N	240	W	pick cut rock to shank
500	7.1	N	240	W	substantial dust production
500	7.1	N	240	W	
700	7.1	N	240	P	
700	7.0	N	240	P	
700	7.4	N	240	P	wheel shattered
700	7.2	N	240	W	new wheel, some chipping
700	7.2	N	240	W	brief white hot spot
700	7.1	N	240	W	brief yellow hot spot developed

JP S2 DRY

RPM	CH_4%	IGNITION	TIME (s)	PICK	COMMENTS
500	7.1	N	240	P	chipping of sample
500	7.2	N	240	P	pick cut rock to shank
500	7.0	N	240	P	pick cut rock deeply to shank level
500	7.2	N	240	W	substantial dust production
500	7.2	N	240	W	substantial dust production
500	7.0	N	240	W	substantial dust production
700	7.3	N	240	P	substantial dust production
700	7.4	N	240	P	substantial dust production
700	7.4	N	240	P	substantial dust production
700	7.0	N	240	W	substantial dust production
700	7.2	N	240	W	substantial dust production
700	7.5	N	240	W	substantial dust production

JP S4 DRY

RPM	CH_4%	IGNITION	TIME (s)	PICK	COMMENTS
500	7.1	N	240	P	
500	7.0	N	240	P	some chipping
500	7.2	N	240	P	
500	7.2	N	240	W	wheel shattered
500	7.1	N	240	W	new wheel
500	7.3	N	240	W	
700	7.4	N	240	P	brief yellow hot spot
700	7.0	N	240	P	
700	7.1	N	240	P	
700	7.2	N	240	W	pick cut rock to shank
700	7.5	N	240	W	
700	7.2	N	240	W	

Table 6.3 (continued):

JP S4 WET 6.5% H_2O

RPM	CH_4%	IGNITION	TIME (s)	PICK	COMMENTS
500	7.2	N	240	P	
500	7.0	N	240	P	
500	7.2	N	240	P	
500	7.2	N	240	W	
500	7.5	N	240	W	some chipping
500	7.3	N	240	W	
700	7.6	N	240	P	
700	7.5	N	240	P	some fine dust produced
700	7.1	N	240	P	dust increases
700	7.5	N	240	W	substantial dust production
700	7.5	N	240	W	substantial dust production
700	7.4	N	240	W	wheel shattered

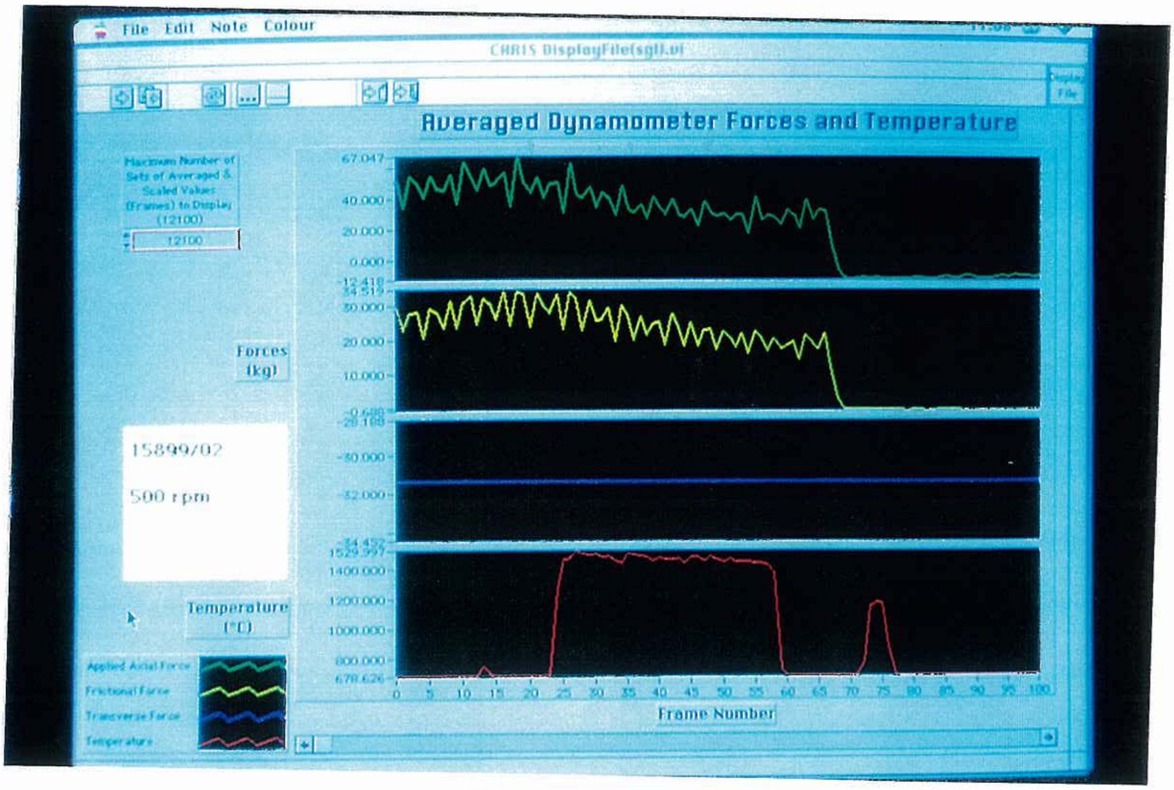
6.5 Instrumented test runs

A series of "proving" runs was carried out on the instrumentation developed for the project, especially the dynamometer system. Details of these are given in Section 4.3 above.

Once these were complete, a number of tests were carried out to test the response of the system to the different variables (applied force, wheel speed) on a number of different rocks, both in air and in an ignitable methane atmosphere. Only rock-on-rock friction was able to be tested at this stage, although appropriately prepared metal sliders, and even metal or ceramic wheels, could also be tested if necessary.

Output from the instrumented runs was intended to provide continuous data on the normal (vertical) force, tangential shear (frictional) force and lateral (sideways) thrust, along with the hot-spot temperature, developed in the course of each individual test (Figure 6.7). For all tests, coefficient of friction was calculated as shear force divided by normal force. The results of this testing are given in Appendix A1.3.

A problem was encountered, as discussed above, with one of the strain gauges in the dynamometer during testing, so that lateral thrust data were not recorded in most test runs. The absence of such data did not significantly affect the test results, as analysis of only the two-dimensional (X-Z) situation was sufficient to characterise the forces involved. The time lost in re-installing the relevant components and recalibrating the dynamometer with the new strain gauge did not justify replacement at that time.



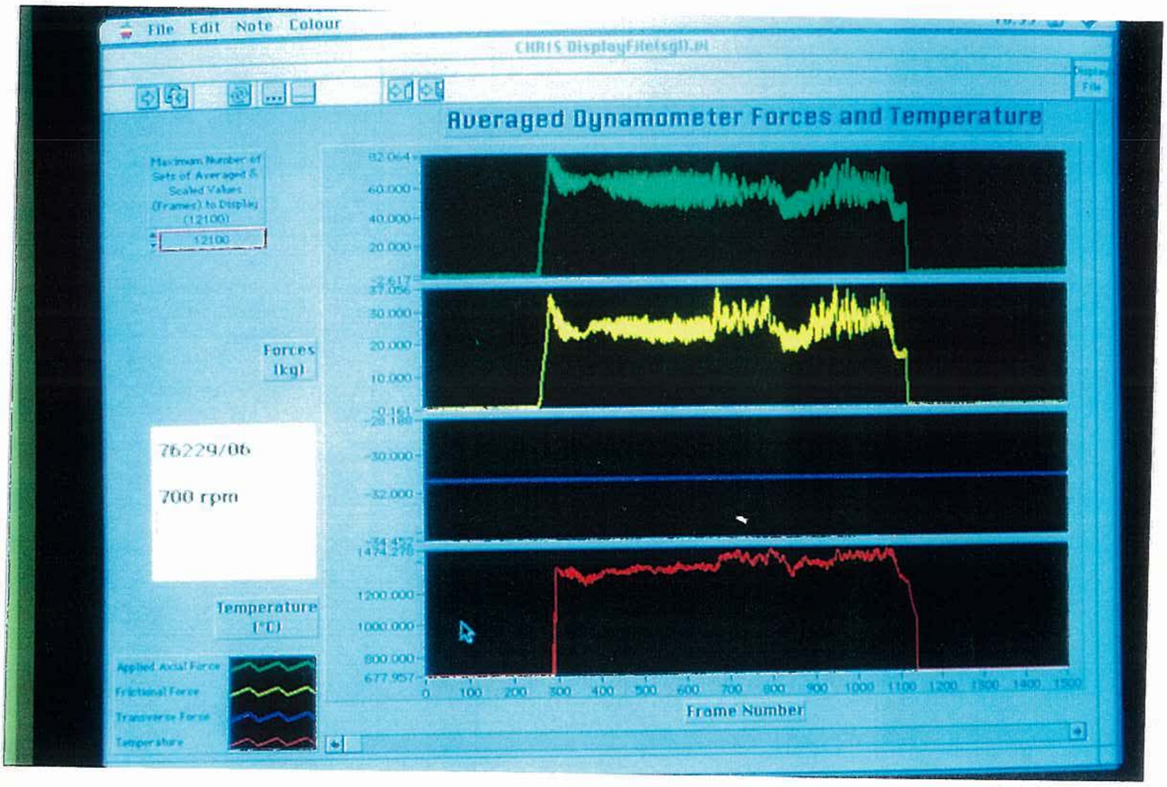


Figure 6.7: Photographs showing output of normal force, frictional force and temperature from typical ignition test runs (see Figure 4.1 for further explanation).

- Top photo: Sample 15899, tested at 500 RPM.
- Bottom photo: Sample 76229, tested at 700 RPM.

Although only a relatively small number of samples has been tested to date, and many of these through a combination of circumstances have a relatively high IGCAT value, preliminary graphs summarising comparisons between the various parameters derived from the program are given in Figures 6.8 to 6.17. Correlations derived from these graphs are discussed briefly below:

6.5.1 Coefficient of Friction

With the exception of one unusually low result of around 0.2, the mean coefficient of friction determined from the instrumented rock-on-rock test runs varied from 0.4 to around 0.8. Maximum values are significantly higher, including many values greater than 1; however, these mostly represent short-term peaks derived from stresses generated when the wheel jammed or "hit a bump" in the course of the individual test runs.

Notwithstanding the unusually low value for one test resuly, the average values for coefficient of friction seem to be significantly higher for rocks with IGCATs of between 3 and 5 than for rocks with lower IGCAT values (Figure 6.8). However, the sample suite covered by the program did not include many low-IGCAT rocks, and further work is needed to confirm this trend. Such a correlation is consistent with a higher rate of heat generation due to development of an increased frictional force, for a given combination of normal load and wheel speed.

It should be noted that the coefficient indicated is a coefficient of dynamic friction, rather than static friction. For most rocks it is also significantly higher than the value of 0.5 taken to generate physical power data for incendivity characterisation of ceramic materials by Tolson and Brearley (1995).

6.5.2 Mean and Maximum Temperature

Partly due to the moving nature of the hot spot in the ignition tests, capture of temperature data associated with ignitions has proved to be the most difficult aspect of the entire research program. The data gatehred to date, however, indicate that the hot spot temperature in each individual test run builds up in a very short time (typically less than one second), and although fluctuating by up to 100°C remains relatively constant beyond that time.

Mean temperatures of 1200 to 1500°C were observed for the rocks tested. Maximum temperatures, commonly but not always associated with the actual gas ignition, are generally 50 to 100°C higher. Such temperatures are consistent with the interpretations of Boland et al. (1994) derived from thermocouples embedded in a cutter-pick apparatus.

Graphical plots of mean temperature against IGCAT (Figure 6.9) suggest a generally positive correlation between the two. However, the amount of information on rocks with a low IGCAT value is limited, partly because of the nature of the sample suite and partly because many of these rocks do not generate a hot spot that can be reliably

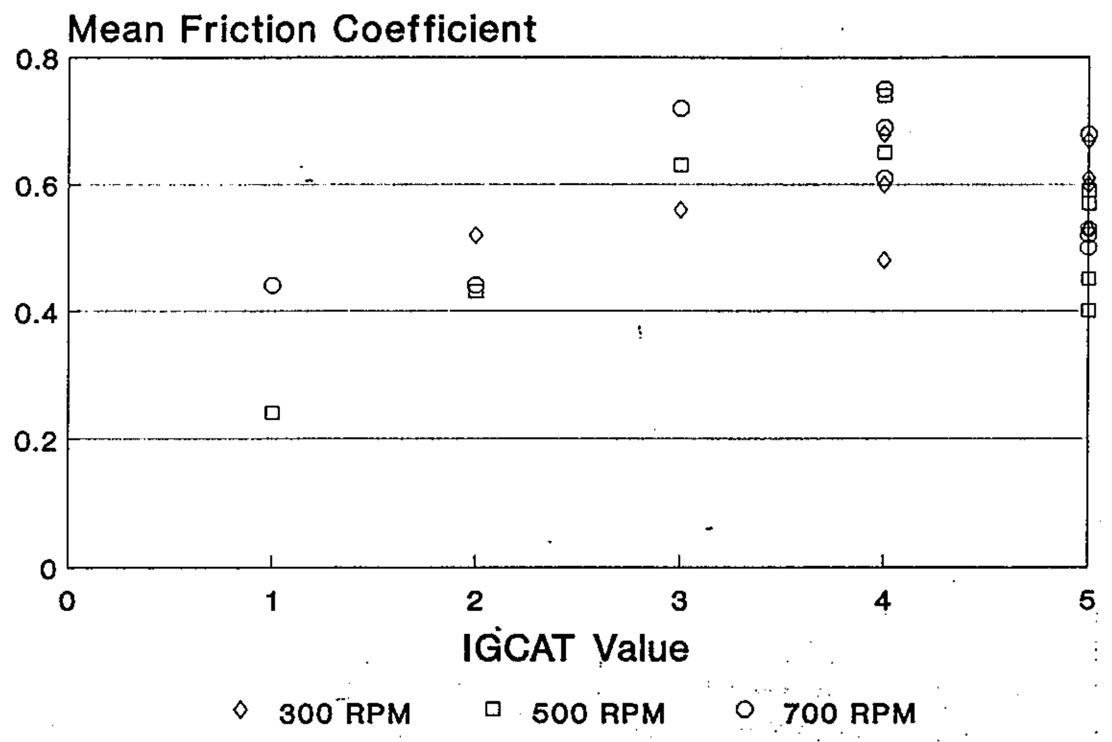


Figure 6.8: Correlation between mean coefficient of friction and IGCAT value for instrumented test runs.

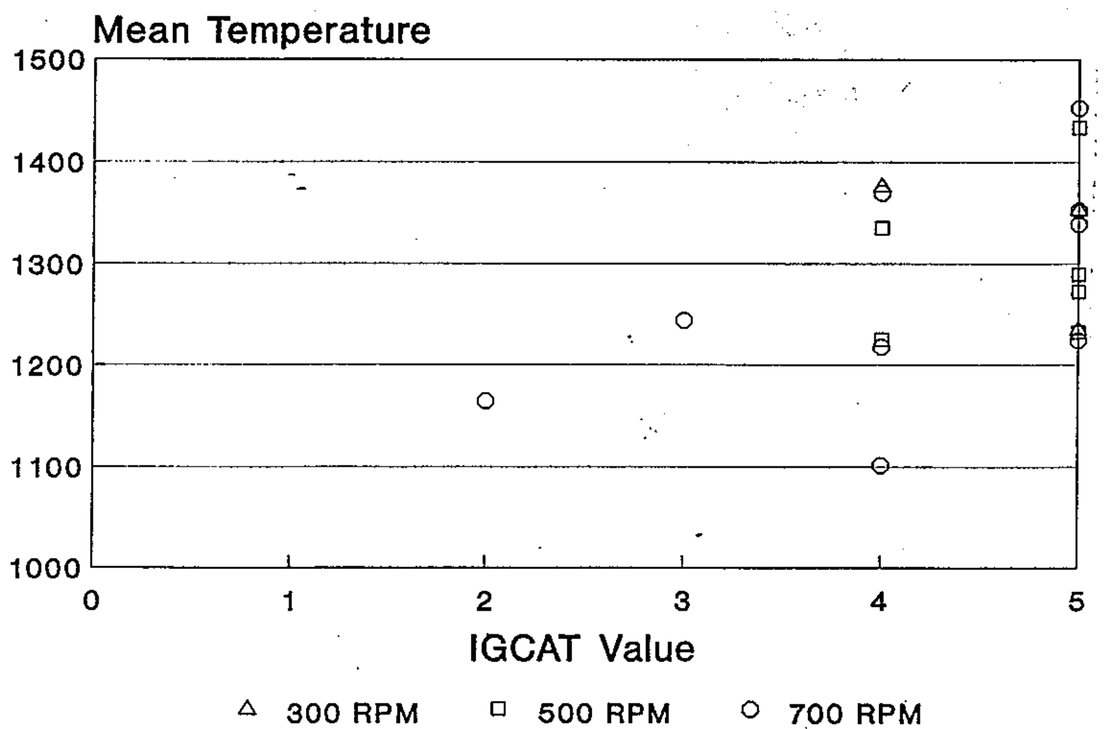


Figure 6.9: Correlation between mean hot-spot temperature and IGCAT value for instrumented test runs.

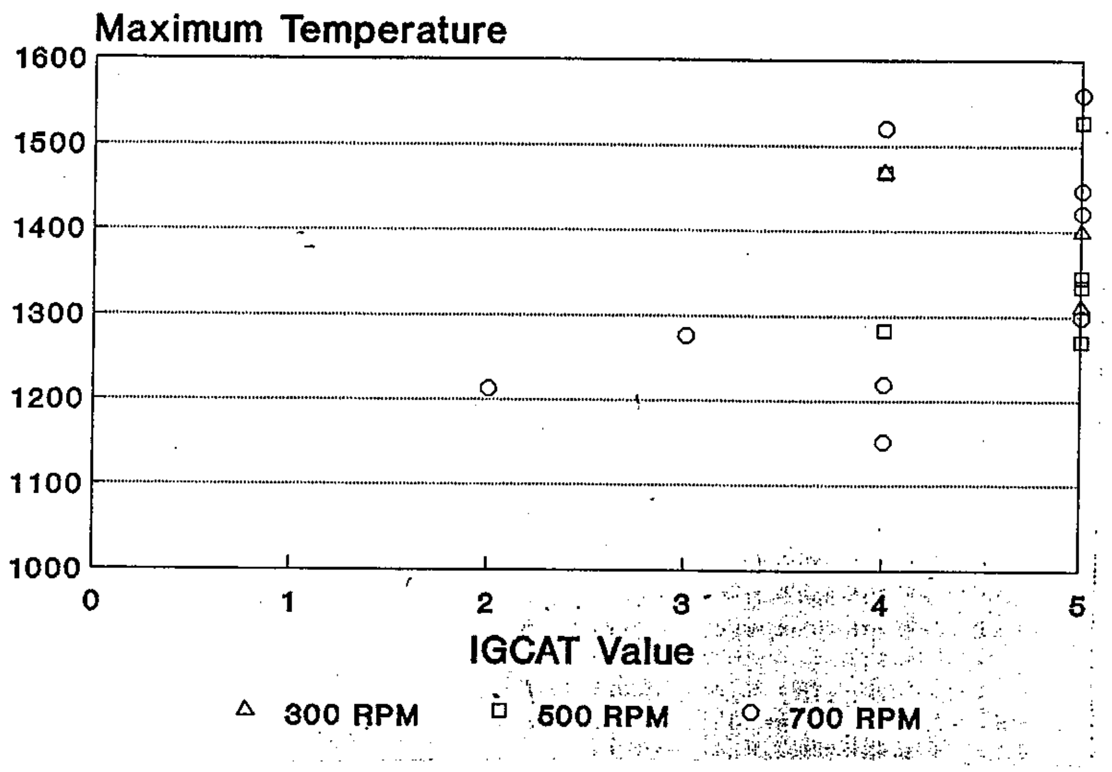


Figure 6.10: Correlation between maximum hot-spot temperature and IGCAT value for instrumented test runs.

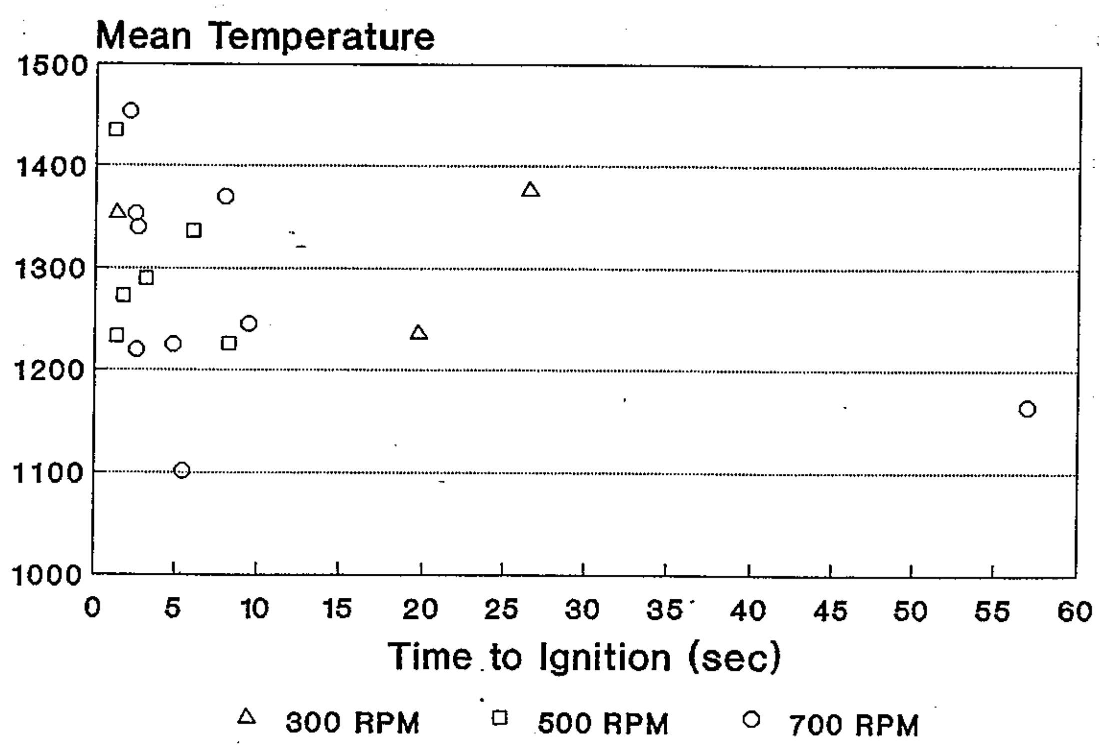


Figure 6.11: Correlation between mean hot-spot temperature and time to ignition for instrumented test runs.

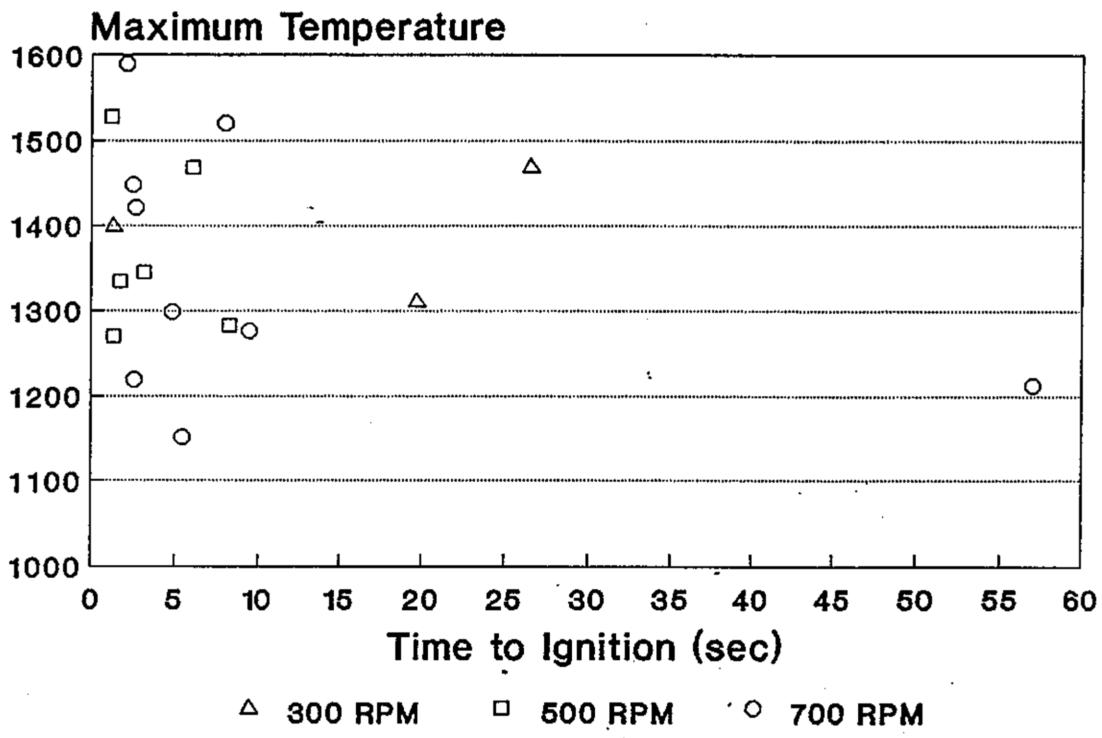


Figure 6.12: Correlation between maximum hot-spot temperature and time to ignition for instrumented test runs.

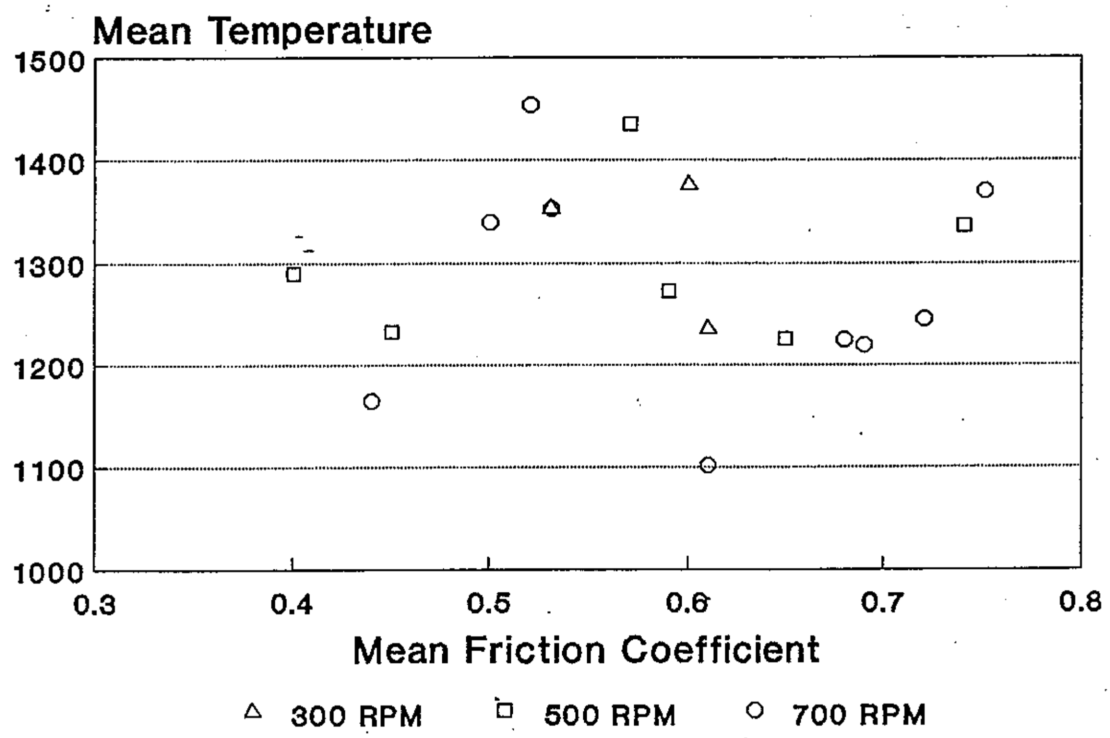


Figure 6.13: Correlation between mean hot-spot temperature and mean coefficient of friction for instrumented test runs.

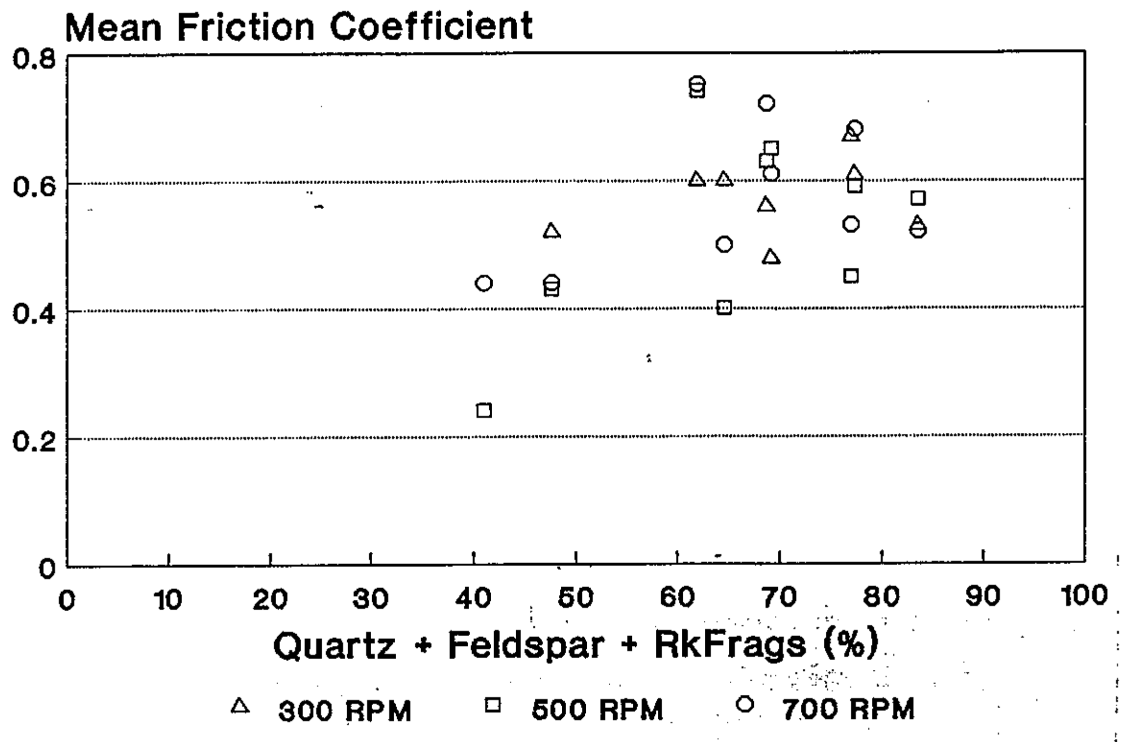


Figure 6.14: Correlation between mean coefficient of friction and petrographic composition (quartz + feldspar + rock fragments) for instrumented test runs.

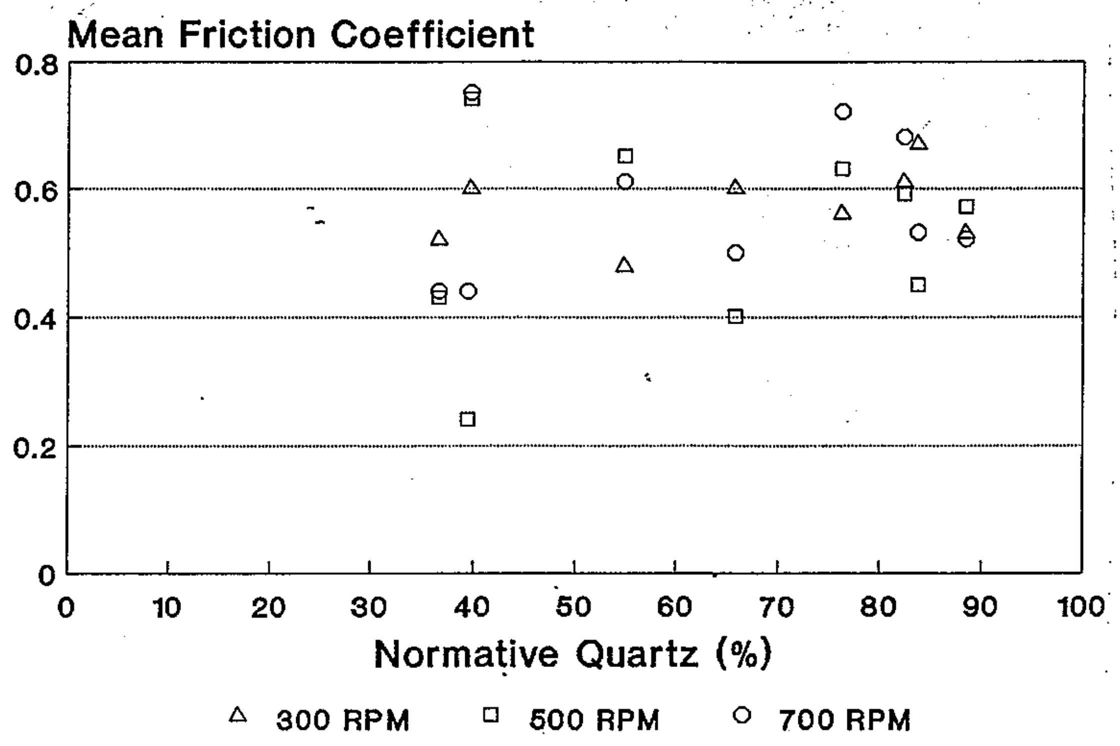


Figure 6.15: Correlation between mean coefficient of friction and normative quartz content (estimated by SEDNORM) for instrumented test runs.

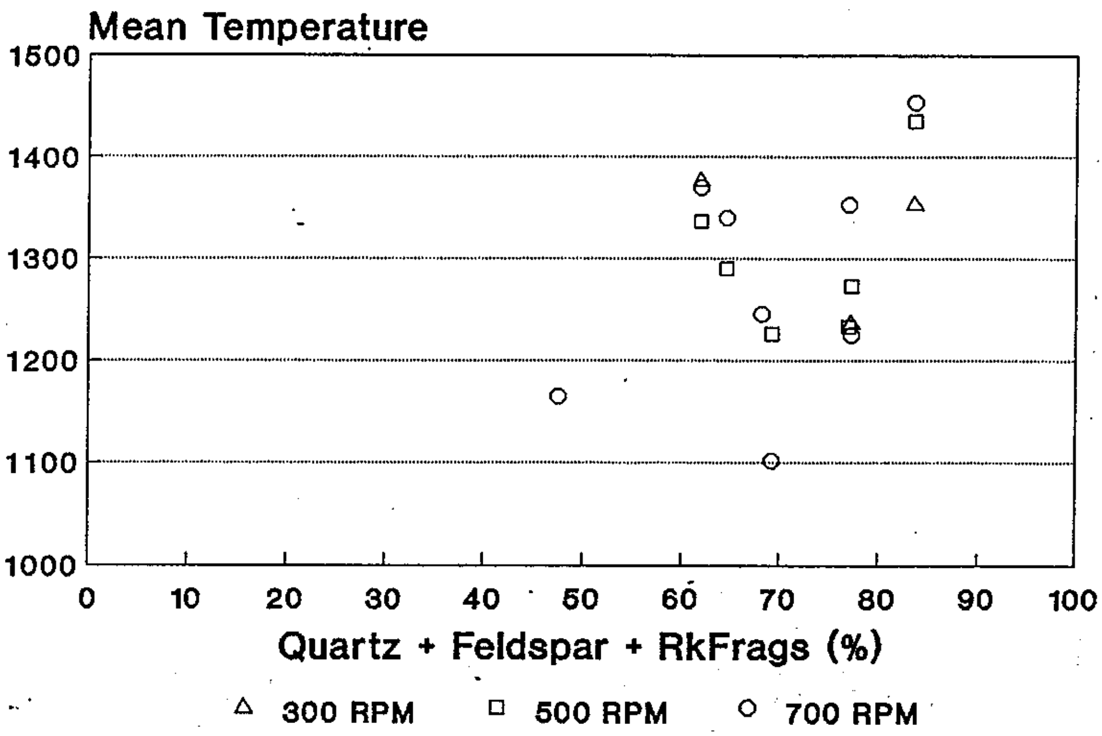


Figure 6.16: Correlation between mean hot-spot temperature and petrographic composition (quartz + feldspar + rock fragments) for instrumented test runs.

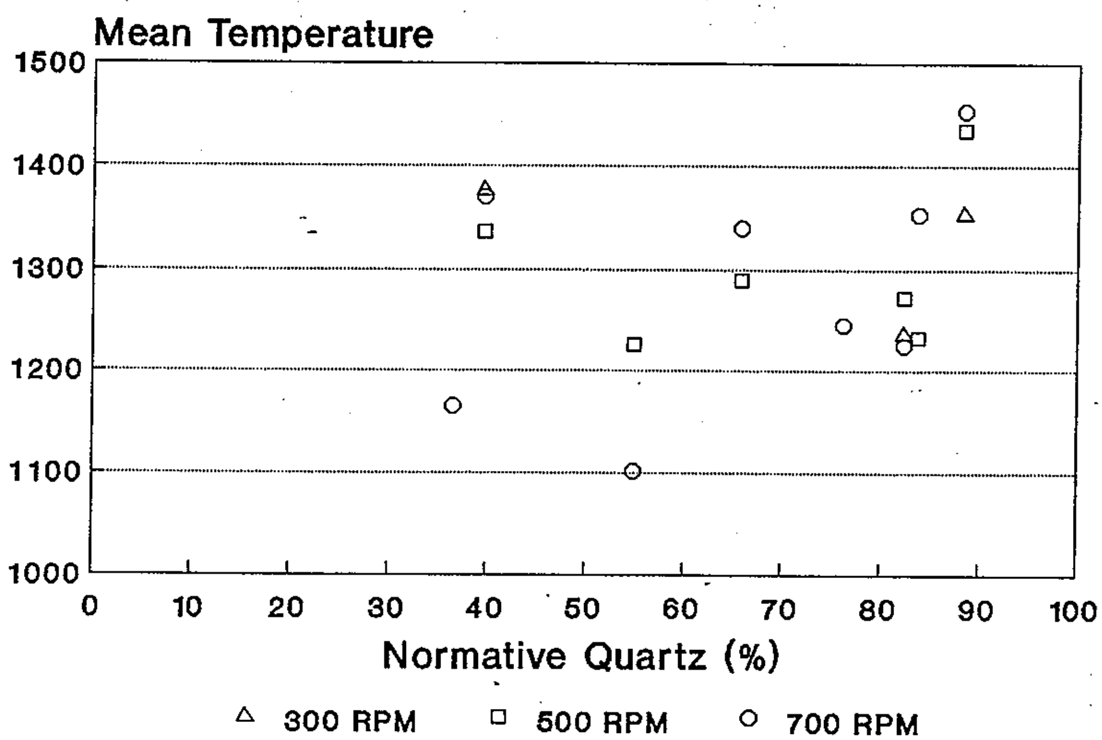


Figure 6.17: Correlation between mean hot-spot temperature and normative quartz content (estimated by SEDNORM) for instrumented test runs.

tracked by the pyrometer system. The maximum temperature generated in each run shows a similar correlation (Figure 6.10), although the data are more widely spread for the IGCAT 4 materials.

Neither the mean nor the maximum temperature data seem to show a significant correlation with the time taken for ignition to take place in the test rig (Figures 6.11, 6.12). The tests in which the highest temperatures were developed do appear to have among the shortest ignition times, but both short and long times to ignition are associated with the other temperature values.

No particular correlation is apparent between the mean coefficient of friction and the mean temperature (Figure 6.13). This, as well as the rapid onset of temperature development, suggests that other factors are involved in determining the maximum temperature reached in an individual test run.

6.5.3 Petrographic Indices

Graphs correlating mean coefficient of friction against the total percentage of quartz + feldspar + rock fragments as determined by point counting and against the percentage of quartz as estimated by normative analysis of the chemical composition of the rock samples are given in Figures 6. 14 and 6.15. Although a slight positive correlation is suggested by these charts, the data (especially the normative quartz data) are highly scattered, and no significant conclusions are drawn at this stage.

Graphic plots showing the correlation between mean temperature and the same petrographic indices are given in Figures 6.16 and 6.17. A slight positive correlation is also suggested from these plots, but the high degree of scatter and the limited extent of the data set render significant conclusions difficult at this stage.

Further investigation using the instrumentation is necessary to test the extent to which the correlations between IGCAT and the various petrographic indices can be explained by quantification of rock frictional or temperature properties.

6.6 Ignition Tests with Unmatched Wheels and Sliders

Experience in sample collection shows that it is not always possible to obtain a rock sample, particularly a sample free of mechanical discontinuities, sufficiently large to prepare a 150 mm diameter wheel for use in the UNSW ignition test rig. This became particularly apparent in the investigation of the ignition at South Bulga colliery in November, 1993. The horizon known to have caused the ignition was identified by inspection of the coal face and samples as large as possible were collected by colliery staff. The material, however, was heavily fractured and very brittle, and despite careful handling a wheel for use in ignition testing could not be produced.

In an attempt to derive some data on relative incendivity for this material, a series of tests was carried out using a wheel prepared from a different rock type, a lithic sandstone with mid-range (IGCAT = 3) ignition properties. Sliders of the siliceous coal from South Bulga, together with sliders of the sandstone from which the wheel was made and several other rock types, were tested against this wheel in a 7% methane atmosphere and the times to ignition (if any) noted. The results obtained (Table 6.4) indicated a range of incendive behaviour consistent with the nature of the materials under test. Ignition categories were assigned to each material on the basis of the behaviour of each slider, and from the results the South Bulga material, with a relatively long time to ignition at 300 RPM, was assigned an IGCAT value of 4 to 5.

It was recognised that the use of an unmatched wheel in frictional ignition testing, if successful with a wider range of materials, had potential to allow evaluation of relative incendivity in situations where a wheel of the test material itself cannot be obtained. It would be valuable, for example, as a basis for testing slim-hole (50 mm) exploration drill cores, along with brittle or hard to sample rocks such as the South Bulga material.

For this reason a further study was initiated, and subsequently completed as a separate project by Coates (1995). This follow-up work involved preparing several wheels from a metamorphic quartzite, quarried for industrial purposes at Marrangaroo, near Lithgow, New South Wales. Although not a rock likely to be found in coal mines, the quartzite had the advantage over a colliery sample of being available in relatively large quantities if necessary. As the subject of on-going extraction and associated quality control, it was anticipated that if this material proved suitable a long-term supply would be available for future ignition testing.

A large quartzite sample was obtained from the Marrangaroo quarry (courtesy of Metromix Pty Limited) and three wheels of approximately 150 mm prepared in the UNSW Mining Engineering laboratory. Because the rock had a visible foliation and therefore possibly one or more inherent planes of mechanical weakness, PVC rings, sliced from a length of 150 mm diameter PVC pipe and split longitudinally, were placed around the ends of each wheel and secured by hose clamps (Figure 6.18) to provide reinforcement against breakage during rotation. A strip of bare rock was exposed on the cylindrical surface of each wheel, however, for use in the testing operation.

A test program was instituted using sliders of six different rock types against the quartzite wheel. A constant load of 2.26 kg was applied to the control handle of the rig, which was increased at the slider - rock wheel interface by the mechanical advantage of the loading system. The results of the individual tests are summarised in Table 6.4.

As with the tests described above using the lithic sandstone wheel, a range of responses in terms of times to ignition was developed. Several samples gave short and relatively consistent ignition times and hence were assigned a high IGCAT value from the tests. Others (e.g. a mudstone sample from German Creek) did not give rise to any ignitions (despite the high incendivity of the quartzite wheel), or gave ignitions only at relatively high wheel speeds in the test program.

A further series of tests was run using a rock wheel made from granite, a rock determined in the 1987-1990 program to have an ignition category of 3 (sample 1120

Table 6.4: Results of ignition tests involving un-matched wheels and sliders (after Coates, 1995).

Time to Ignition and IGCAT Values

Appin Sandstone Wheel

RPM	M1 claystone	A1 sandstone	FB1 quartzite	SB10 siliceous coal
700	*	12	2	2
500	*	28	15	11
300	*	*	35	30
IGCAT	1	3	4	4-5

Marrangaroo Quartzite Wheel

RPM	CL1 sandstone	OCk sandstone	M2 siltstone	SBu2 carb. s/stone	GCk mudstone	Gst sandstone
700	101	9	0.4	9	*	1
500	*	5	0.9	1	*	14
300	*	37	59	*	*	21
IGCAT	2	5	5	3-4	1	5

Hartley Granite Wheel

RPM	CL1 sandstone	OCk sandstone	M2 siltstone
700	*	1.4	NT
500	NT	5	*
300	NT	44	*
IGCAT	1 Note 1	5	2 Note 2

Notes:

* = No ignition

NT = Not tested

Note 1 - Not tested at slower speeds since no ignition at high speed

Note 2 - Short test runs (<30 sec) due to slider breakage. Not tested at 700 RPM due to loss of slider material in previous tests

Test data for matched wheels and sliders

RPM	CL1 Sandstone	A1 Sandstone
700	29	12
500	110	28
300	*	*
IGCAT	3	3

in Ward et al., 1991). Only a few of the samples tested against quartzite were able to be included in this program, however, because in many instances all of the slider material available had been consumed in the quartzite test runs. Most of the samples that were tested against granite, moreover, could only be tested in short individual runs due to the limited amounts of slider material available.

Significant differences were noted in the behaviour of the individual sliders against the granite, compared to the quartzite wheel. Sample CL1, which ignited the methane after 100 seconds at 700 RPM against quartzite, did not ignite the methane at 700 RPM against granite. The result, however, is inconclusive, since the test against granite was only able to run for about 50 seconds before the last remaining slider was fully ground away. Previous testing of sample CL1 against a wheel of the same material (see main data set) gave rise to ignitions at both 500 and 700 RPM, suggesting that both the quartzite and the granite wheels were somewhat less effective than the matched wheel and slider configuration.

Sample M2 was also unable to be tested for an adequate length of time against the granite wheel, due to consumption of slider material. No ignition was obtained over a 20 second test run at 500 RPM, despite the fact that sample M2 had caused an ignition at the same speed after less than 1 second against quartzite. No ignition was obtained after 30 seconds at 300 RPM, but this is inconclusive at almost 60 seconds were required for ignition at the same speed with the quartzite test wheel. There was insufficient slider material left from these experiments to allow a test against granite at 700 RPM.

The third sample, a sandstone from Oakey Creek mine in Queensland, provided similar high-IGCAT results with both the granite and the quartzite wheels.

The general conclusion from this series of studies is that a relative grading can be established for materials in terms of frictional incendivity by using an unmatched slider-wheel combination. The results, while separating highly incendive from less incendive materials, do not, however, necessarily give the same IGCAT values as tests against a wheel prepared from the same rock sample. In view of the potential benefits in testing small or brittle samples, however, further research in this area is warranted.

7 COLLABORATION WITH OTHER FRICTIONAL IGNITION LABORATORIES

As part of the work program for the present study, contact was developed and maintained with the Safety in Mines Testing and Research Station (SIMTARS) of the Queensland Department of Minerals and Energy at Redbank, Qld, and with the CSIRO Division of Exploration and Mining at Pinjarra Hills.

The visit to SIMTARS was to obtain a first-hand update on frictional ignition research at that organisation, following on from the work completed under NERDDP sponsorship by Golledge et al. (1991). It was also intended to discuss the possibility of comparative incendivity testing of rock materials using the different methodologies developed at the Queensland centre. The equipment at SIMTARS was, however, in the process of being rebuilt, and was not expected to be available for a comparative study before the end of the present project in late 1995.

The visit to CSIRO followed on from a visit to UNSW during 1993 by a CSIRO representative and a Japanese delegation, to review progress at UNSW with frictional ignition research. Following that visit, UNSW was invited to collaborate with CSIRO and the Coal Mining Research Centre of Japan in a program of frictional heating experiments related to rock cutting using a series of Japanese rock samples. A total of four Japanese rock samples were subsequently tested at UNSW, using both rock-on-rock and pick-on-rock techniques, and the results incorporated into the database of the present research project. One of these was the sample tested by Boland et al. (1994) in rock-cutting studies discussed in the literature review above, and on-going contact has been retained with CSIRO on frictional ignition research since that time.

In conjunction with travel to the United Kingdom for other purposes, Dr D.R. Cohen, a member of the project team, visited the laboratories of the Health and Safety Laboratory at Buxton, and those of International Mining Consultants Limited (formerly associated with British Coal) at Burton-on-Trent, during 1994 to discuss the frictional ignition programs of both UNSW and UK research institutions. Presentations were made by Dr Cohen outlining progress with the UNSW investigation, and inspections were made of the respective institutions' research facilities. Copies of reports, and a videotape illustrating frictional ignition from pick cutting processes, were provided to UNSW as additional reference sources.

Also in conjunction with other University business, A/Prof C.R. Ward visited the laboratories of the DMT Gesellschaft fur Forschung und Prufung (formerly Bergbau Forschung) in Essen, Germany during August, 1995, for extensive discussions with the company on its frictional ignition research. These included inspection of a large-scale ignition testing facility at Dortmund (discussed separately elsewhere in this report), and of the company's petrological and mineralogical analysis facilities for incendivity and abrasiveness assessment. A suite of five German rock samples was subsequently supplied to UNSW for comparative incendivity testing; as with the Japanese materials the results obtained from these were incorporated into the present project database.

While in Europe Professor Ward also attended the 26th International Conference of Safety in Mines Research Institutes in Katowice, Poland. Papers presented at that conference relevant to the project included a review of frictional ignition experience in South African coal mines (Phillips, 1995), French research on improvements in the use of water sprays on mining equipment (Godard et al., 1995) and incendivity testing in Britain of zirconia and other ceramic materials (Tolson and Brearley, 1995). Follow-up contact was subsequently made with Professor Phillips of Witwatersrand University and Dr Tolson of the Health and Safety Laboratory in Buxton, to amplify aspects of their respective research programs.

7.1 International Mining Consultants Limited, Bretby, UK and Health and Safety Executive, Buxton, UK.

In September, 1994, D.R. Cohen visited the research facilities of International Mining Consultants Limited (IMCL), which incorporates the former research and consulting division of British Coal, at Bretby in the United Kingdom, and also the laboratories of the Health and Safety Executive at Buxton. Both these establishments have been involved recently in experimental work on frictional ignition, and possess a variety of friction ignition test rigs.

At both establishments, seminars were presented on the work at UNSW, and both the methodology and results of Australian and British work were discussed with research staff.

IMCL operates a large friction ignition test rig which is designed to test continuous miner picks on large rock slabs. The test chamber occupies a volume of around $3m^3$ and is filled with an 8% methane mixture. A large slab of rock (usually a sandstone), 60 cm wide and up to 1m long, is fixed to a large hydraulic slider (Figure 7.1). Picks (Figure 7.2) are mounted on cylinders and rotated at speeds approximating normal operating conditions (a tangential pick velicity of around 1 ms^{-1}). In the test observed, the continuous miner was started and the slider-mounted rock slab moved towards the head at around 0.2 ms^{-1}. On contact the pick excavated the rock to around 1cm depth, and the slider speed ensured each new pick attack was on a fresh surface. Multiple tests were performed along new tracks in the slider. The contact between pick and rock was recorded using a high-speed video apparatus.

A video copy of a test observed by Dr Cohen at IMCL was retained. In this test, each pick strike was accompanied by the release of both unaltered and glazed rock materials. A number of strikes occurred before one fragment of red-hot and glazed selvedge of rock (1 x 2cm) triggered an ignition. A slow motion analysis of the video indicated the heated particle emenated from the back of the pick and was moving away from the contact for up to 0.1s before the ignition occurred.

The high speed video recording indicated that hot and glazed selvedge fragments were released from the surface with each pick strike. A portion of these glaze fragments adhered to the pick (probably due to welding) and the remainder were scattered around the test chamber. Despite the glazed fragments being red-hot, the gas did not ignite in either test until the release of a sufficiently large fragment (or possibly the

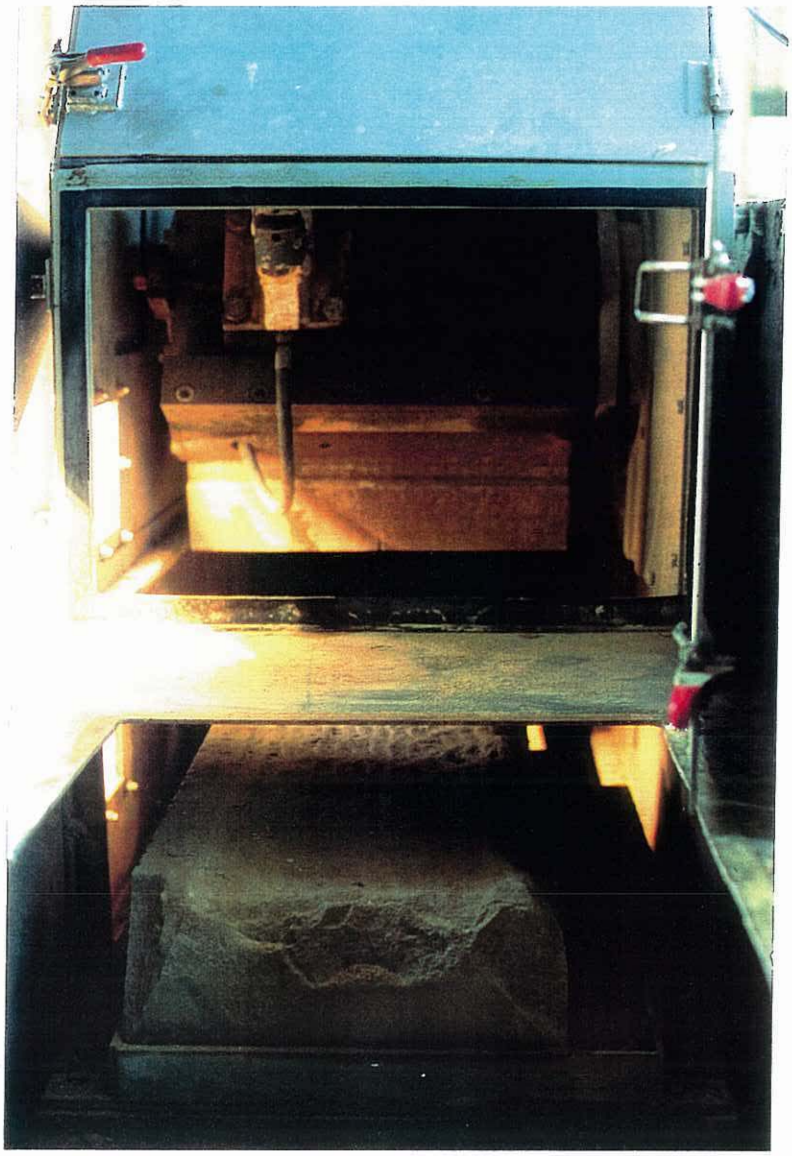


Figure 7.1: General view of ignition chamber used by International Mining Consultants, Bretby, for pick-on-rock studies. The rock sample can be seen at the bottom of the picture, and a pick mounted on its cutter drum at the top.

Figure 7.2: Close-up view of pick used in International Mining Consultants test rig, showing wear developed after a test program.

combination of sufficient size versus temperature). The methane explosion appeared to emanate from the glazed fragment rather than the pick or rock surfaces.

7.1.1 Comparison between IMCL and UNSW rigs.

The IMCL rig is designed to test equipment rather than categorise rocks. Various items, such as picks, are tested against a standard rock (a quartzose arenite).

The main use of the rig is to test impact events against fresh rock surfaces, rather than continuous frictional events against the same surface (which changes over time due to abrasion and glazing). In this respect, the IMCL rig should be viewed as complementary to the UNSW rig.

The advantages of the frictional ignition test rig at IMCL, with respect to the UNSW rig, as a means of categorising rocks are:

- the capacity to test actual mining equipment (or slightly scaled-down models) against a rock surface under "normal operating condition" and determine the effects of changes in operations on the probability of an ignition occurring.

- the provision of high resolution and detailed data on the test conditions via the high speed video system.

The disadvantages are:

- a large slab of rock is required for the test (although mounting of smaller samples as mosaic of plates set in a concrete slab appeared possible).

- it is difficult to establish criteria for generating a comparative ignition risk category beyond a simple ignition/non-ignition classification (though the number of strikes before an ignition could be a suitable variable).

- in the present configuration, forces and temperature are not measured.

The IMCL team is operating a contract for Spanish coal mines on frictional ignitions. The project is sponsored by an arm of the European Union. The staff at IMCL have offered some access to EU documentation, which would otherwise be unavailable to non-member countries. IMCL offereed to test some samples used in the work at UNSW. However, their rig was not able to handle the small sample dimensions used at UNSW, and transport of 100 kg samples of Australian coal mine rocks to the United Kingdom was not feasible.

Although no tests were observed in operation at Buxton, this facility contains a number of test rigs. These range from rigs similar to that at UNSW to a larger version in which samples of rock are held against the rim of a large rotating wheel of Derby Sandstone 2m in diameter.

Frictional ignition work on British mines only occurs in response to actual mine incidents suspected of being related to frictional ignition occurrences.

7.2 DMT Gesellschaft fur Forschung und Prufung, Essen, Germany

The DMT Gesellschaft für Forschung und Prufung is part of a major a private German company with diverse interests in mining. It embraces the former Bergbau-Forschung organisation, a well-known producer for many years of quality mining research.

DMT and its predecessors have maintained an active frictional ignition research program for some time. Current research in the area is driven mainly by efforts to prevent the elimination of roadheaders from German coal mines due to the higher pick-on-rock ignition risk with the cutting forces used by equipment of this type. The principal researcher (Group Leader) in charge of this program is Dipl. Ing. Walfried-Erik Marx.

7.2.1 Frictional Ignition Test Facility

A major part of the DMT research involves use of a large frictional ignition test facility, located in Dortmund, some 30 km east of Essen itself. This unit has a gas chamber some 2 metres high, 2 metres wide and around 1.5 metres deep, similar in proportions to an Australian garden shed. The chamber has three concrete sides and a concrete roof; the fourth side is covered by a plastic sheet, which blows out when an ignition occurs (Figures 7.3, 7.4).

Rock samples tested in the unit are sawn blocks approximately 700 mm x 500 mm x 500 mm, supplied by a local quarrying company. Although those in use at the time of the visit were ironstained and therefore slightly oxidised, they are said to represent typical sandstones of the Ruhr coalfield sequence.

The rock is cut by picks on a metal wheel of around 1.5 m diameter (Figure 7.5), turned by a drive unit, similar to the drive unit on conventional mining machines, in an adjoining room (Figure 7.6). The axis of the wheel is horizontal and the wheel itself vertical. The wheel can be adapted to hold between two and 24 picks, with water sprays introduced at strategic locations if required.

In a routine test, a prepared block of rock is placed on a cradle in front (on the blow-out wall side) of the wheel. This cradle is moved sideways by a worm drive across the face of the wheel in the course of the test, allowing a section of the rock approximately 10 mm deep to be trepanned off the exposed face by the cutting process.

A plexiglass observation window is built into the back wall of the unit (the side away from the blow-out wall), behind the cutting section on the rock face. An infra-red camera has been used in some experiments to provide image analysis data associated with individual cuts, and a movie camera in others to record the impact of individual pick strikes.

Figure 7.3: General view of frictional ignition test facility at DMT Gesellschaft fur Forschung und Prufung, Dortmund, Germany, showing plastic blow-out wall in place. A rock sample block, after cutting in the chamber, can be seen in the foreground.

Figure 7.4: Same view as Figure 7.3 at the instant of gas ignition. The scale of the ignition produced can be clearly seen.

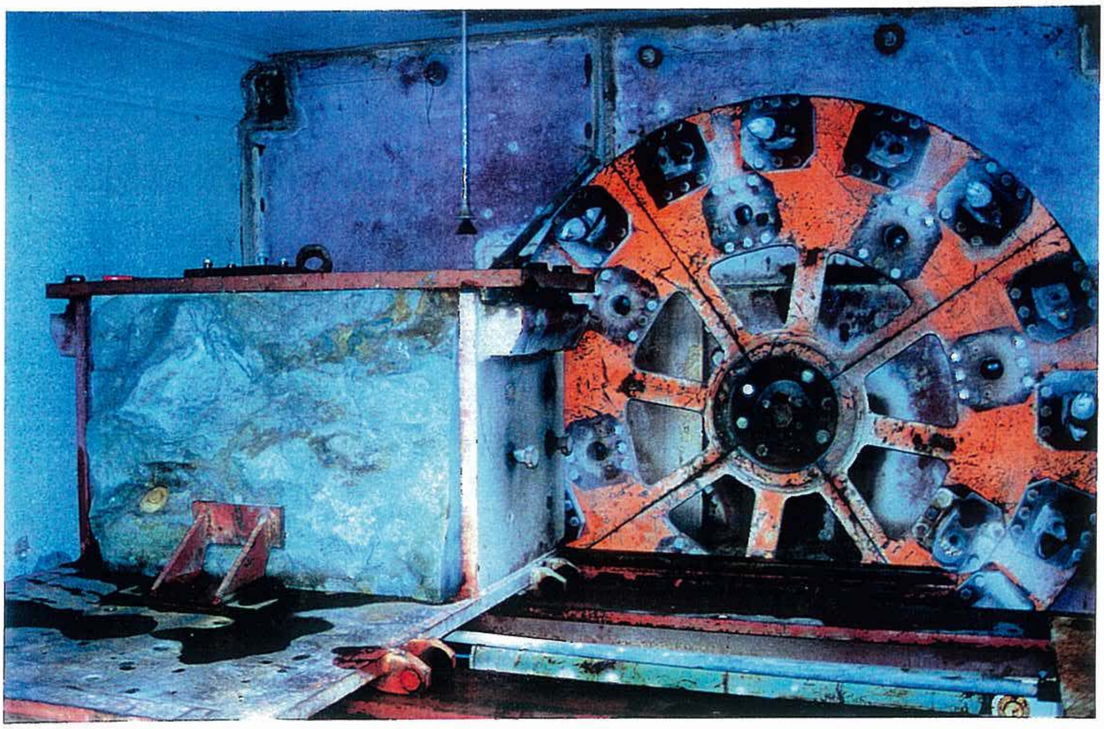


Figure 7.5: Interior of DMT frictional ignition test facility, showing rock sample in place and picks mounted on cutter wheel. The rock sample traverses on a cradle across the face of the cutter wheel.

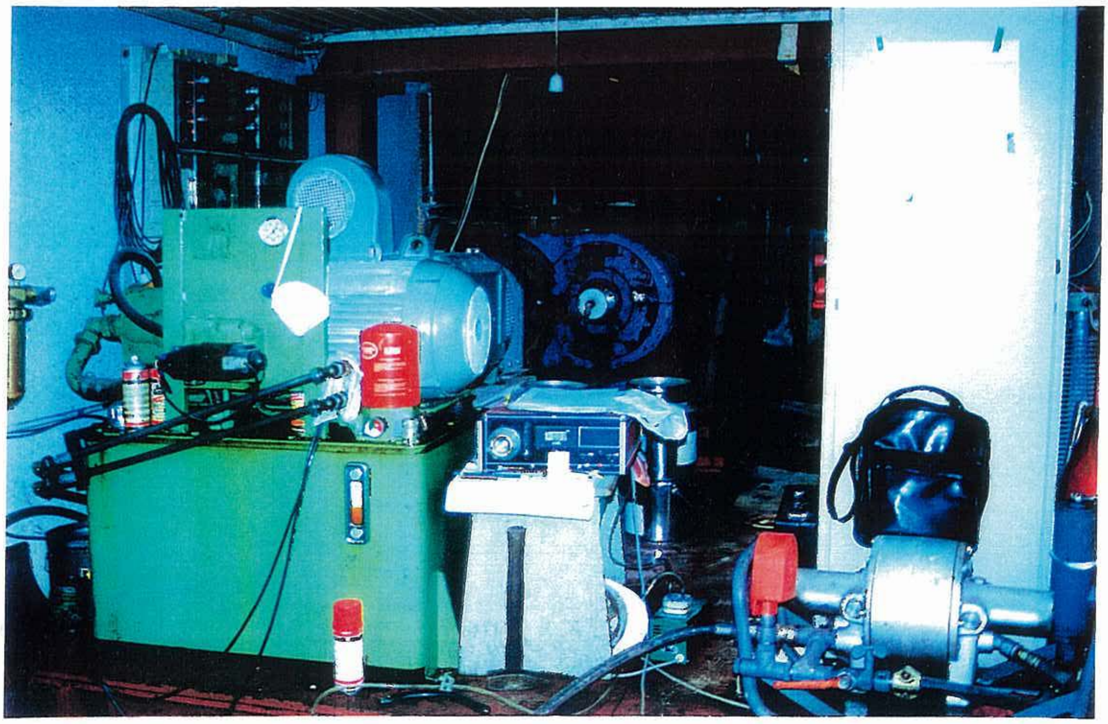


Figure 7.6: Drive unit of the DMT frictional ignition test facility. The ignition chambe itself is located behind a concrete wall at the rear of the picture

The design allows the effects of different pick designs and different water spraying systems to be investigated in an incendive methane atmosphere. This is the principal thrust of the DMT research program. Testing of incendivity of different rock types, although possible, is limited by the relatively large size of the blocks required. Smaller blocks, or composite blocks of concrete faced with the rock under test, have been found not have the same thermal or mechanical properties (strength and cutting resistance), and are not regarded by DMT as a reliable basis for incendivity testing.

The volume of gas ignited in this apparatus is much larger than that ignited in the UNSW test rig. The equipment, although well suited to pick-on-rock testing, is therefore only able to be used at an open site dedicated to mine safety research activities. Testing at Dortmund is restricted to working hours before 1 p.m., to minimise the impact of the ignition noise on residents in houses nearby.

7.2.2 Petrographic Analysis

Like UNSW, DMT use thin-section petrography (point counting) as the basis of evaluating rock materials, both for frictional incendivity and for related abrasiveness assessment. Sandstones from the Ruhr coalfield contain mainly quartz as the framework grains, along with a certain proportion of fresh to altered feldspar and some rock fragments, as well as minor proportions of mica flakes and clay.

Rocks are graded with respect to frictional incendivity on a similar basis to the NCB classification (National Coal Board, 1984). Materials with less than 35% quartz are regarded as having low incendivity potential, those with 35 to 50% quartz as having medium incendivity and those with greater than 50% quartz as having high frictional incendivity potential. Discussion with the chief petrographer, however, indicates that the rock fragments are counted as "quartz" if they are thought to be hard (e.g. low birefringent, siliceous types) or "clay" if soft (e.g. high birefringence, micaceous types). This adjustment gives a better basis for comparison to the UNSW petrographic classification.

DMT also use petrographic data to predict the abrasiveness of rock materials. Weightings are applied to different constituents. The percentage of "quartz" in the rock is multiplied by a factor of 1.0 and that of feldspar by a factor of 0.33; the weighted percentages are then added together to give a petrographic abrasiveness (pick wear rate) indicator (Schimazek, 1976).

A suite of five German rock samples (three quartzose sandstones and two calcareous sandstones) was supplied to UNSW, following this visit, for comparative evaluation of frictional ignition properties. These were subjected to ignition testing in the UNSW test rig, and to petrographic and mineralogical analysis. The data obtained are discussed, along with information from other rocks investigated, elsewhere in this report. Information on the relative incendivity of these materials, as assessed by DMT, has not yet been provided.

7.2.3 Other Ignition Research

Other research at DMT is concerned with the use of water sprays on rock cutting machines to minimise frictional incendivity risk. A modified roadheader has been developed for experimental purposes, with water jets placed behind the individual picks to act as ignition suppressors (Figure 7.7). The use of pulsed water flow has also been investigated, rather than continuous water sprays, as a means of reducing the water requirements for the system and of reducing the softening of floor and other strata by the water runoff from the coal face.

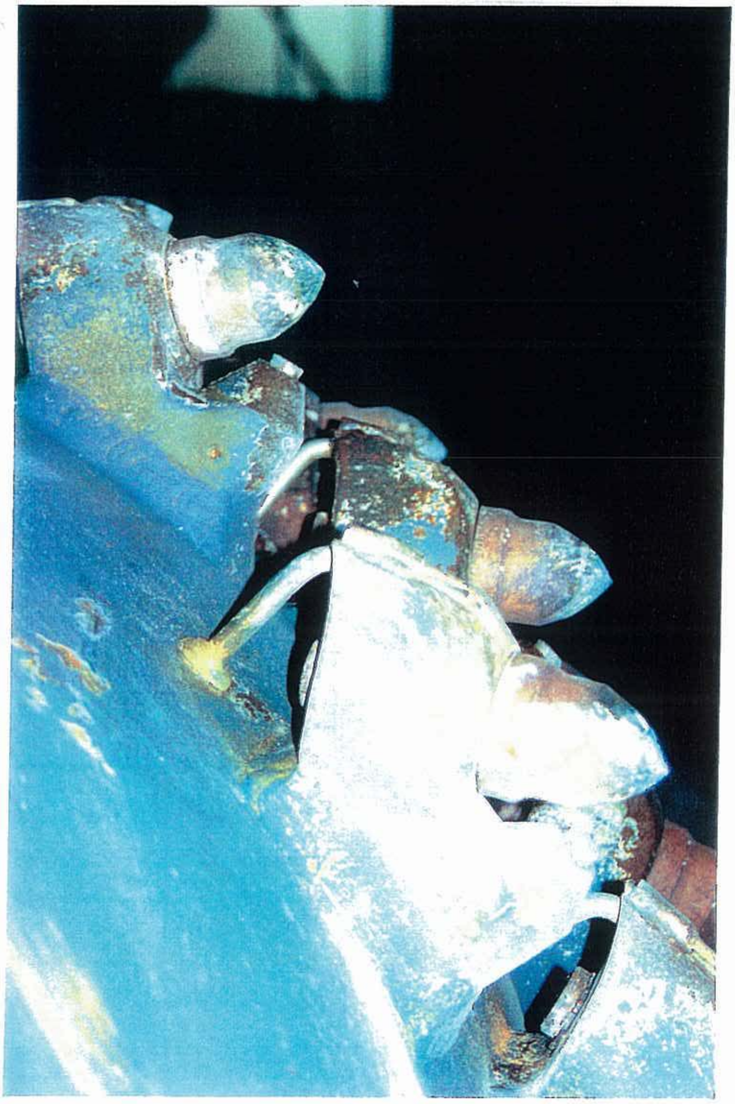


Figure 7.7: Water spray jets located behind picks on experimental roadheader used by DMT Gesellschaft fur Forschung und Prufung.

8 CONCLUSIONS

Investigation of an additional sample suite, including several rock types not previously subjected to ignition testing, has confirmed the correlations between rock composition parameters and frictional incendivity categorisation (IGCAT) developed by Ward et al. (1990, 1991a,b). Some minor revisions have been made to the relevant equations and diagrams as a result of the present study, and updated information is included in this report.

Attention is drawn in particular to the ignition risk associated with silicified bands in coal seams, at least some of which occur in conjunction with intra-seam tuffaceous claystone horizons. Methods for identifying these materials at the face or in drill holes, and of predicting their occurrence at mine sites, should be further investigated.

A sophisticated suite of instrumentation has been developed by the present study to investigate the frictional forces and temperatures developed in laboratory testing on a more quantitative basis. The instrumentation has been calibrated and tested on rocks from both Australian and overseas coal mines, and found to give satisfactory, reproducible results. The instrumentation is also capable of adaptation for other mine-related purposes, such as heating associated with machine cutting experiments.

Rock-on-rock tests using this instrumentation show average dynamic friction coefficients of between 0.48 and 0.75. Maxima are considerably higher, due to transient effects such as surface irregularities and wheel jams.

Temperatures of between 1100 and 1550°C have been measured at the hot-spot in rock-on-rock studies. These temperatures are developed quickly (< 1 second) in the course of individual ignition tests. They are typically well above the value normally required to ignite a methane-air mixture in laboratory conditions.

Analysis of video records from individual ignition tests show that methane ignition mostly originates slightly behind the hot-spot developed from rock-on-rock friction in the test rig. This is consistent with the hot-spot itself acting as the ignition source, rather than incandescent particles (sparks) generated by the frictional heating process. The point of origin behind, rather than at the hot-spot is explained by a time delay in development of the ignition reaction.

Although only limited data have been obtained at this time, broad positive correlations are tentatively suggested between the rock ignition category (IGCAT value) and mean friction coefficient and mean hot-spot temperature. These correlations, however, need to be further tested before meaningful conclusions can be drawn. Correlations between friction coefficient or hot-spot temperature and rock composition parameters also require further testing in the instrumented ignition rig.

Testing of brittle materials, such as siliceous coal, or materials where large samples are not readily available, can also be facilitated by friction against a wheel of an unmatched rock type with known IGCAT characteristics. This has great potential to simplify the ignition testing process, and should be further investigated if possible.

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APPENDIX A

Analytical and Ignition Test Results

Appendix A1.1 X-ray fluorescence geochemical data

Sample no.	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	SO_3
Appin 3	73.06	0.68	13.19	3.97	0.09	0.63	0.48	0.79	1.66	0.12	0.02
JP-S1	68.67	0.41	15.05	2.34	0.07	0.75	2.00	3.20	3.01	0.13	0.01
JP-S2	77.77	0.01	0.41	2.43	0.09	0.50	4.57	0.37	0.01	0.04	0.26
JP-S4	60.05	0.67	14.51	3.24	0.03	0.54	6.83	2.73	1.68	0.04	0.17
CL1	83.85	0.44	8.01	1.48	0.02	0.28	0.14	0.07	1.48	0.05	0.00
15899	92.25	0.06	3.42	1.90	0.00	0.05	0.05	0.29	0.94	0.06	0.10
16253	50.51	0.06	6.38	3.79	0.06	0.67	19.20	0.94	2.22	0.08	0.01
76229	90.20	0.88	5.79	0.25	0.00	0.03	0.00	0.18	1.21	0.05	0.03
76230	90.06	0.05	5.48	0.33	0.00	0.06	0.03	0.25	2.75	0.05	0.00
76231	45.29	0.09	3.90	5.43	0.00	0.98	22.50	0.55	0.88	1.96	0.22
9501 GC	77.07	0.61	11.41	2.58	0.03	0.52	0.31	0.94	2.52	0.06	1.13
Gord 2	79.33	0.40	10.59	1.92	0.02	0.28	0.14	0.69	2.57	0.03	0.08
Moura 2	65.23	0.71	17.60	2.39	0.02	0.50	0.49	2.74	5.20	0.15	0.02
9502 NL	71.75	0.50	12.96	3.33	0.02	0.52	1.79	0.39	0.94	0.09	0.05
Oaky Ck 1	60.99	0.94	17.22	5.44	0.04	0.88	0.36	0.86	3.18	0.07	0.15
Oaky Ck 2	64.34	0.74	13.99	6.07	0.05	0.89	0.39	0.94	2.72	0.06	0.15
SB 10	79.11	0.02	0.40	1.11	0.03	0.01	0.03	0.44	0.03	0.02	0.50
Sth Bulli 2	64.09	0.86	21.71	0.68	0.00	0.34	0.05	0.48	3.00	0.04	0.01

Appendix A1.2 Mineralogy based on sedimentary normative composition, by mass

Sample no.	Quartz	Feldspar	Illite/Mica	Kaolinite	Calcite	Magnesite	Apatite	Sid./Hem.	Pyrite	Halite	Anatase
Appin 3	53.8	8.5	17.1	15.4	0.0	0.0	0.3	4.2	0.0	0.0	0.7
CL1	76.1	0.0	12.8	8.2	0.1	0.6	0.1	1.5	0.0	0.0	0.5
15899	88.3	0.0	8.0	0.8	0.0	0.0	0.1	1.9	0.1	0.7	0.0
16253	36.5	14.5	9.4	0.0	34.1	1.4	0.2	3.9	0.0	0.0	0.0
76229	83.7	0.0	0.0	14.6	0.0	0.0	0.1	0.2	0.0	0.5	0.9
76230	82.3	5.4	11.8	0.0	0.0	0.0	0.1	0.3	0.0	0.0	0.0
76231	39.4	0.0	8.8	2.5	35.5	2.1	4.6	5.4	0.3	1.4	0.0
9501 GC	60.4	7.9	21.5	4.2	0.4	1.1	0.1	2.3	1.5	0.0	0.6
Gord 2	65.7	5.9	22.3	2.8	0.2	0.6	0.0	2.0	0.1	0.0	0.4
Moura 2	39.6	8.3	28.1	13.9	0.5	2.1	0.2	6.2	0.2	0.0	0.9
9502 NL	54.8	3.4	9.6	23.8	3.1	1.1	0.2	3.4	0.0	0.0	0.5
Oaky Ck 1	39.6	7.7	28.6	14.5	0.5	2.0	0.2	5.8	0.2	0.0	1.0
Oaky Ck 2	47.2	8.4	24.6	9.6	0.6	2.0	0.2	6.5	0.2	0.0	0.8
Sth Bulli 2	35.1	0.0	30.9	31.1	0.0	0.0	0.0	0.7	0.0	1.3	0.9

Appendix A1.3 Mineralogy based on point counting

Sample no.	QM	QP	Fel	Mica	RF	Carb	Op	Matrix	Other
JP-S1	22.0	8.0	6.0	4.0	12.0	2.0	2.0	42.0	2.0
JP-S2	0.0	23.0	0.0	0.0	0.0	2.0	60.0	10.0	5.0
JP-S4	20.0	5.0	3.0	1.0	10.0	22.0	6.0	32.0	1.0
CL1	34.8	5.7	0.5	1.7	27.6	4.0	1.0	23.7	1.0
15899	61.3	16.7	0.0	5.7	5.5	0.0	3.0	7.8	0.0
16253	26.2	3.5	7.7	1.2	10.1	48.2	0.0	3.1	0.0
76229	73.1	1.7	0.0	2.1	2.1	0.0	0.5	20.2	0.3
76230	61.8	6.7	8.7	2.7	0.0	0.0	0.0	20.1	0.0
76231	22.3	0.5	0.0	0.2	18.1	56.2	0.7	0.5	1.5
9501 GC	49.2	0.0	4.0	20.1	2.7	2.2	4.7	16.1	1.0
Gord 2	50.1	4.0	3.2	7.0	7.2	1.0	5.7	21.3	0.5
Moura 2	31.8	3.0	4.2	11.0	22.8	1.0	8.5	17.7	0.0
9502 NL	27.3	0.0	5.0	1.5	36.8	6.7	1.0	21.0	0.7

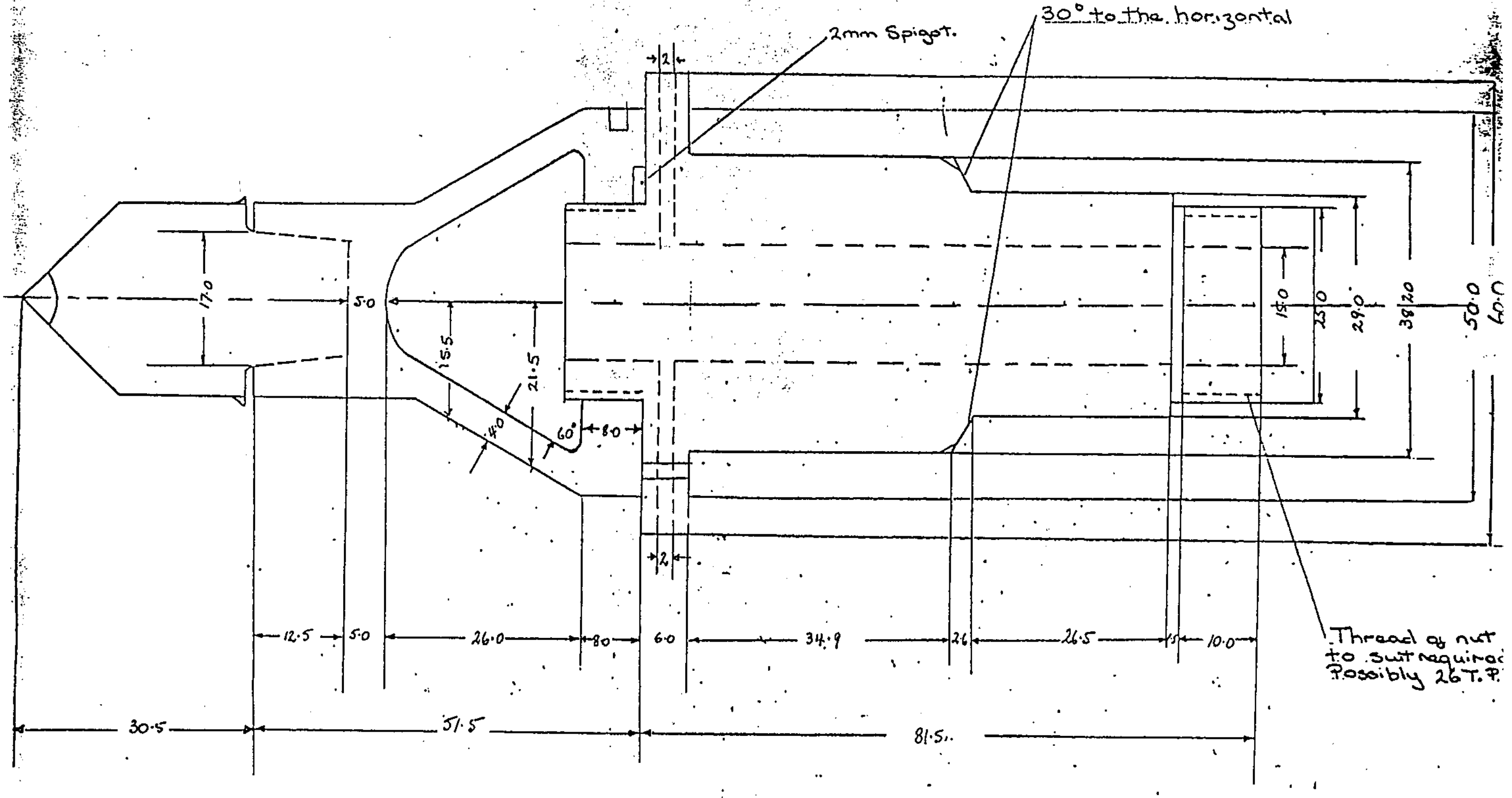
Appendix A1.4 Physical data

Sample no.	IGCAT	Time to ignition 300 rpm	Time to ignition 500 rpm	Time to ignition 700 rpm	Mean coefficient of friction 300 rpm	Mean coefficient of friction 500rpm	Mean coefficient of friction 700 rpm	Max coefficient of friction 300 rpm	Max coefficient of friction 500 rpm	Max coefficient of friction 700 rpm	Mean temperature 300 rpm	Mean temperature 500 rpm	Mean temperature 700 rpm	Max temperature 300 rpm	Max temperature 500 rpm	Max temperature 700 rpm	LOI
Appin 3	4.0	ni	1.5	2.5	0.68	0.65	0.69	1.69	0.99	0.93	nd	nd	1218	nd	nd	1218	6.24
JP-S1	2.5	ni	ni/92.0	32.0	nt	nt	nt	nt	nt	nt	nt	nt	nt	nt	nt	nt	4.11
JP-S2	3.0	ni	73.7	28.3	nt	nt	nt	nt	nt	nt	nt	nt	nt	nt	nt	nt	14.05
JP-S4	2.0	ni	ni	36.5	nt	nt	nt	nt	nt	nt	nt	nt	nt	nt	nt	nt	9.74
CL1	3.0	ni	41.6	9.4	0.56	0.63	0.72	0.80	1.10	1.05	nd	nd	1244	nd	nd	1275	3.15
15899	5.0	1.3	1.1	2.0	0.53	0.57	0.52	0.78	0.87	0.75	1353	1434	1453	1399	1527	1558	0.95
16253	2.0	ni	nt	56.9	0.52	0.43	0.44	0.79	0.55	0.64	nd	nd	1164	nd	nd	1212	17.06
76229	5.0	1.6	1.3	2.4	0.67	0.45	0.53	1.32	0.57	0.88	nd	1232	1352	nd	1268	1447	1.66
76230	5.0	19.7	1.7	4.8	0.61	0.59	0.68	1.08	0.83	1.40	1235	1272	1224	1310	1334	1297	1.38
76231	1.0	nt	ni	ni	nt	0.24	0.44	nt	0.46	1.18	nt	nd	nd	nt	nd	nd	17.94
Gord 2	5.0	4.6	3.1	2.6	0.60	0.40	0.50	1.02	0.52	0.63	nd	1289	1339	nd	1344	1421	2.79
Moura 2	4.0	ni/26.5	6.0	7.9	0.60	0.74	0.75	1.12	1.02	1.41	1376	1335	1369	1469	1468	1519	4.47
9502 NL	4.0	ni	8.2	5.4	0.48	0.65	0.61	0.80	1.34	1.27	nd	1225	1101	nd	1281	1151	6.35
SB 10	* 4.5	30.0	11.0	2.0	nt	nt	nt	nt	nt	nt	nt	nt	nt	nt	nt	nt	19.08
Sth Bulli 2	nt	nt	nt	nt	0.68	nt	0.56	1.30	nt	0.86	nd	nt	nd	nd	nt	nd	9.55

Time to ignition:	seconds
Temperature:	degrees Celcius
LOI:	% loss on ignition at 1050 deg C
nd:	not determined
ni:	no ignition
nt:	not tested
*	IGCAT determined with "standard" sandstone wheel

APPENDIX B

Dynamometer Information



PICK-DYNAMOMETER (CONE).

APPENDIX C

Petrographic Description of Silicified Coal Sample

APPENDIX C1.1

PETROGRAPHIC DESCRIPTION OF SILICIFIED COAL SAMPLE (SB-10) FROM SOUTH BULGA COLLIERY

C.R. Ward and P.J. Christie

Hand Specimen Description

Dark grey, hard, siliceous, fine grained mudstone. Sparks readily.

Thin Section Description

The section is composed of fragments containing well defined organic cell structures infilled mainly by quartz (silica), along with minor scattered siderite nodules to 1mm. Many of the quartz fillings contain inclusions of coalified organic material. Fractures are chalcedonic, although some quartz-filled cleats are present, composed of sub to euhedral grains up to 0.25mm.

The silica filling the cells appears to be variable with three main types observed:

1. Polyblastic - well preserved cell walls (tracheids) infilled by fine grained silica. In some cases the layered structure of the tracheid is replicated in silica. These are less common than the following types of observed silicification.

2. Oligoblastic - well preserved tracheids with single quartz crystal infillings. These tend to be slightly strained under crossed polars.

3. Hyperblastic - tracheids ruptured by growth of multiple fine quartz crystals. Possibly original trydimite stabilised by degradation to quartz.

   In addition there are pronounced differences in the compaction of the macerals around the quartz. Some macerals are largely unaffected whilst others are compacted to elongate shapes.

Microscopic Structure

There is a strongly developed primary planar fabric defined by the alignment of tracheids and axial parenchyma containing coalified organic matter.

There is some evidence of concentric layering with alternating zones of oligoblastic and hyperblastic structures. These may relate to the original stem structure. The former consist of well preserved cells infilled with single quartz grains and the latter are elongate deformed ruptured cells infilled with fine silica. The less compacted oligoblastic material may represent the more permeable heart wood whilst the highly compacted hyperblastic zones could result from silicification of the less permeable outer stem and bark.

Alternatively, these structures may relate to different stages of diagenesis, one of fine grained trydimite (now altered to quartz) and one of single coarse grains of quartz. If trydimite was the original silicate material then as it degraded into quartz the growth of many small crystals would lead to rupturing of the surrounding tracheids.

Siderite nodules deform the surrounding wood cell structure and often exhibit boundaries of euhedral fine quartz grains.

Chemical Composition

X-ray fluorescence analysis indicates the following chemical composition:

OXIDE WT.%	SB10
SiO_2	81.02
TiO_2	0.039
Al_2O_3	0.378
Fe_2O_3	0.684
MnO	0.004
MgO	BLD
CaO	0.008
Na_2O	BLD
K_2O	BLD
P_2O_5	0.007
LO1	18.15

BLD = below level of detection

Total carbon (analysed by LECO CNS2000 elemental analyser) is 14.6%; sulphur is 0.31%

X-ray diffraction shows dominant quartz, with traces of kaolinite and siderite. Quantitative x-ray diffractometry indicates 53+ 5% crystalline quartz.

Origin

A biogenic origin for the silica is discounted, since the silicifications would surely be more ubiquitous in distribution had this been a major source of silicification. However, there may have been some contribution from siliceous phytoliths within the coal forming plants.

The relative absence of kaolinite precludes a detrital or pyroclastic origin, as this is the major mineral in the surrounding non-coal sequence.

The small fractures infilled by chalcedonic material and the presence of small quartz cleats infilled with sub to euhedral quartz are unequivocally of late diagenetic origin.

The sideritic nodules appear to post date the original silicification and compaction.

One possible diagenetic model is where silica-saturated ground waters infiltrated the peat beds after burial, perhaps concentrated due to the underlying diagenetic trap formed by the 'cow pat' claystone horizon. Another possibility is that the silica was released during alteration of the underlying claystone band. An early stage of oligoblastic/polyblastic quartz silicification was followed by compaction and concurrent hyperblastic trydimite silicification. Later diagenesis resulted in chalcedonic fracture fillings and quartz cleats.

References

Buurman, P., 1972. Mineralisation of fossil wood. *Scripta Geol.*, 12, pp 1-43.

Sykes, R. And Lindqvist, J.K., 1993. Diagenetic quartz and amorphous silica in New Zealand coals. *Org.Geochem.*, 20, n6, pp 855-866.

Figure C1.1: Thin-section photomicrograph showing wood-grain structure in silicified coal sample. Organic matter is black; silicified cell cavities (quartz) are white.

Figure C1.2: Close-up of section of Figure C1.1, showing detail of cell structure.