SPONTANEOUS COMBUSTION OF SOME QUEENSLAND COALS

By

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ABSTRACT

Incidents associated with spontaneous combustion of coal have resulted in the loss of many lives and considerable capital and equipment. Nevertheless, the factors controlling the propensity of coal to spontaneous combustion are not clearly understood and there is a need for research to study the effects of rank, petrography, moisture contents, etc.

This has been attempted in a study of the propensities of selected Queensland coals to spontaneous combustion. An adiabatic calorimeter was constructed to study the self-heating of a large number of coals. Chemical and petrographic analyses of the coals were determined and an attempt was made to relate these properties to the self-heating characteristics of the coal. The results show a strong relationship between rank and self-heating characteristics and that petrographic composition of coal may also be of importance.

Some observations on the application of the laboratory results to the practical situation are made as are recommendations for future research.

INTRODUCTION

Spontaneous combustion of coal has been a problem which has plagued the coal mining industry since its inception. It has been the cause of the loss of many lives, much equipment and large reserves of coal.

Wherever coal is mined or stockpiled, there is the possibility that a spontaneous heating will develop, which could result in disruptions to supply schedules, degradation of coal quality, loss of equipment and installations, and of most importance, danger to life.

The very act of mining coal, exposes new surfaces which oxidize, and under conditions which do not allow the heat of oxidation to be dissipated, a spontaneous heating will develop. The rate at which heat can be dissipated from a particular site is determined by many factors including the thermal conductivity of the coal and surrounding strata, the compaction of the coal, the rate of air movement, the ambient temperatures of the air, coal and strata. Because heatings are usually initiated by a combination of such factors, meaningful measurement and evaluation is often very difficult to undertake.

The rate at which heat is produced by the oxidation of a coal is of prime importance in determining if a coal will spontaneously combust. Again, many factors combine to determine this rate, including coal rank, petrography, particle size, moisture content and the extent of previous oxidation. The rate of oxidation is roughly related to rank, however, there appears to be many anomalies to a simple rank ordering of coals because many apparently similar coals have very different propensities to spontaneous combustion.

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It cannot be over emphasised that all coals will oxidize with the possibility of producing a spontaneous heating, and that mining (or storage) factors are the main controls in determining if a heating will develop in a particular place. However, a knowledge of the relative propensities of a coal to spontaneous combust is invaluable when planning method of mining, storage, transportation and stockpiling procedures, and the precautions and procedures to be adopted in the event of a heating developing.

METHODS OF TESTING FOR SPONTANEOUS COMBUSTION PROPENSITY

Many tests have been developed to study the phenomenon of spontaneous combustion, most have developed to provide specific information.

The methods that have been used to study oxidation and self-heating characteristics of coal can be divided into five broad groups, according to the basic principle involved, as detailed below:

1. Direct Observation Methods

Used to determine the storage characteristics of coal in stockpiles from which standard laboratory procedures have developed.

2. Isothermal Methods

Used to study the characteristic rates of oxidation, oxygen consumption and gaseous products, and to determine the heat of oxidation. In this type of test, the temperature of the coal is held constant, and the susceptibility to spontaneous combustion is established from the rate of oxygen consumption.

3. Adiabatic Methods

Used to directly measure the self-heating rates and the gaseous products in relation to the temperature. In this type of test, the temperature of the coal is "paced" by an oven surrounding the reaction vessel which is designed to minimize heat lost. The rate of temperature rise is indicative of the coal's propensity to spontaneous combustion.

4. The Crossing Point Temperature Methods

Used to determine the temperature of "spontaneous ignition".

5. Chemical Methods

Used to measure the rate of oxidation and to investigate the structure of coal.

The type of test used to study the spontaneous combustion process would depend largely upon the information required because each test is suited to the study of particular aspects of the process. The isothermal method is particularly suited to studying the effects of coal particle size, oxygen partial pressure, temperature and flow rates, on the rate of oxidation at selected temperatures. The adiabatic method, on the other hand, is suited to simulating conditions in the mine environment or in a stockpile under which spontaneous combustion is likely to occur. It is useful for determining the self-heating rate of coal (as opposed to the rate of heat production by isothermal methods), and for investigating the effect of rank, petrography, chemical composition and of inhibitors upon self-heating. it can also be used to study the gaseous products of oxidation over an extended range of temperatures.

For these reasons, the adiabatic method was favoured for the test programme described in this manuscript.

THE ADIABATIC TEST METHOD

The conditions under which a coal is likely to spontaneously combust are those in which the heat produced by oxidation cannot be dissipated by conduction convection or radiation to the surrounding strata or atmosphere. These conditions are likely to arise in mine goafs and the peripheral zones of failure of coal pillars, and in coal stockpiles and waste heaps. Air circulation must be sufficient to provide the necessary oxygen but insufficient to dissipate the heat generated. If the heat is generated faster than it can be dissipated, the temperature of the coal will rise, as will the rate of

oxidation and a dangerous situation may develop.

An adiabatic apparatus is designed to sim-
ulate the heat flow conditions described above.
The difficulties encountered with such equipment
are - ensuring the heat losses from the reacting
coal are kept to a minimum and maintaining
accurate temperature monitoring and control.

THE EQUIPMENT

The adiabatic apparatus can be considered
to consist of three essential parts, the react-
ion vessel, the oven, and the controller.

The reaction vessel (see Figure 1) contains
the coal sample and consists of a 250 ml vacuum
flask fitted with a teflon plug. Two glass
tubes pass through the plug, acting as inlet and
exhaust, gas conduits. The inlet tube is longer
and pointed to allow easy insertion into the
coal during loading. During the experiment
oxygen is circulated through the coal sample.

The reaction vessel is connected to the gas
supply and exhaust system by "Quickfit" glass
fittings. The gas tight teflon plug is secured
with a brass clamp and two helical springs
attached to spring clips that support the
reaction vessel.

Five thermocouple leads also pass through
the teflon plug and are secured at the end of
the inlet tube; their functions are described
below.

The reaction vessel is secured on the door
of the oven with two strong spring clips. This
allows easy cleaning, loading and replacement,
if necessary. Mounted between the reaction
vessel and the oven door is a heating coil, 2
metres of 3mm copper tubing (see Figure 2). The
gas supply to the reaction vessel is made to
pass through the heating coil to ensure that the
temperature of the gas is as close as possible
to that of the oven. Three thermocouples are
strapped to the heating coil close to its outlet
end, and with the five thermocouples from the
reaction vessel, pass out through the oven door.

The door of the oven is made to push-fit
into the front of the oven, which is constructed
from a double skin of asbestos cement sheeting.
Fibreglass insulation is placed between these
asbestos sheets to reduce heat loss.

At the back of the oven are located a 500
watt heating element and an air blower. The
power to the heating element is electronically
controlled to ensure that the temperature of the
air is either held constant, or follows the
temperature of the coal in the reaction vessel,
as required. In all, there are eight thermo-
couples and one thermistor located in the oven
and the reaction vessel.

The temperature of the coal and of the oven
are measured using an electronic thermometer.
Thermocouples are connected to a rotary switch
for this purpose so that temperature measurements
can be made without continually altering
thermocouple connections.

An accurate measure of the temperature
difference between the coal sample and the oven
is obtained by using two thermocouples
connnected differentially (back-to-back), i.e.
the electrical output from the pair is proport-
ional to the temperature difference. The output
from these differentially connected thermocouples
is measured by a Keithley digital multimeter
having a resolution of one micro volt.

The remaining thermocouples and the therm-
istor are used by the controller to perform a
series of assigned tasks. The most important of
these is to ensure that the temperature differ-
ence between the coal in the reaction vessel and
the oven is kept to a minimum during an oxidation
test. The temperature of the gas entering the
reaction vessel must follow closely the coal
temperature so that heat losses from the reacting
coal are kept to a minimum. Similarly, heat
losses through the walls of the reaction vessel
(vacuum flask) are kept to a minimum. In this
way, the heat generated by oxidation of the coal
is used to increase the temperature of the coal,
and is not lost to the environment.

The thermistor in the oven is used by the
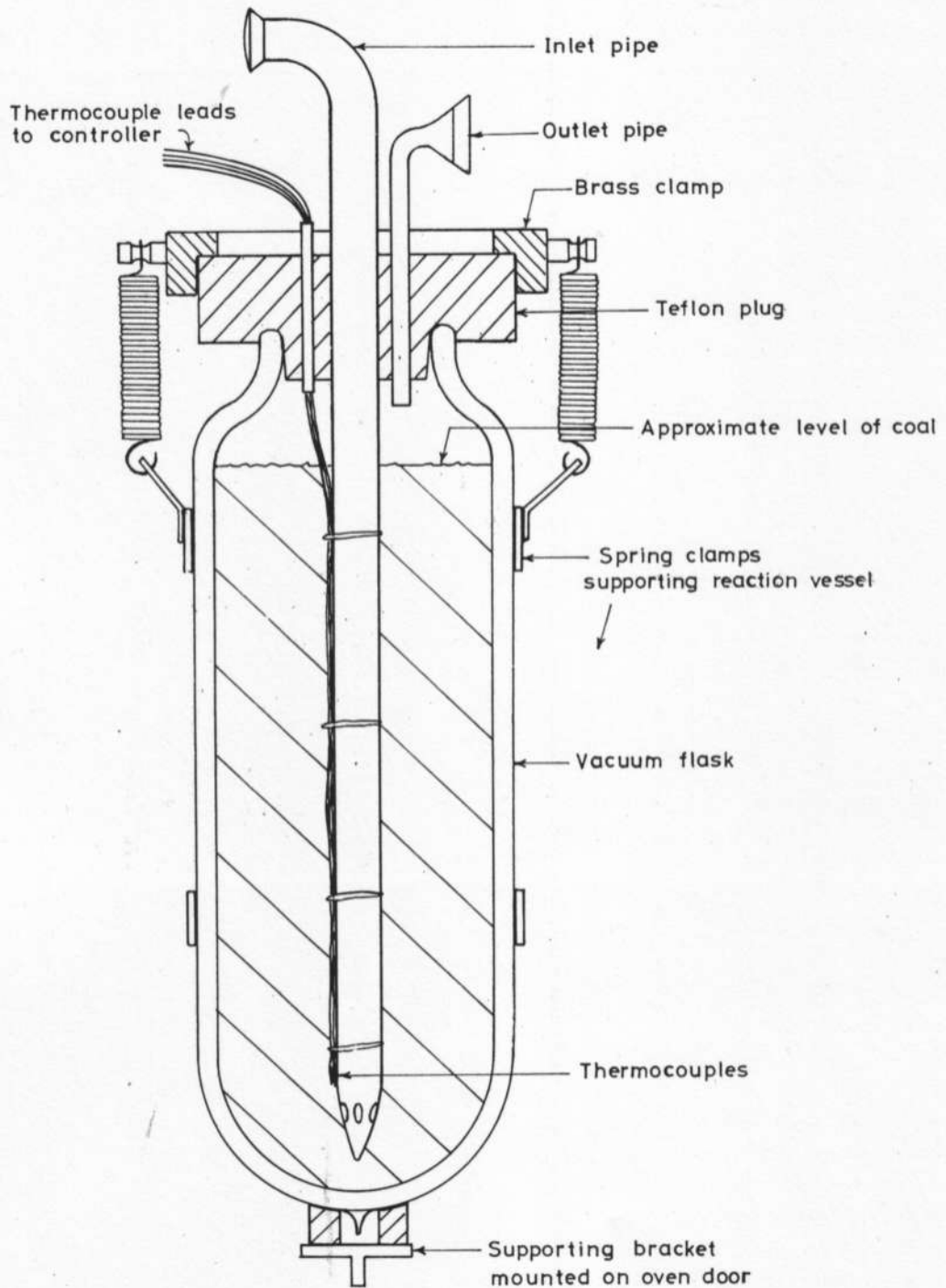controller to hold the temperature of the

Inlet pipe

Outlet pipe

Brass clamp

Thermocouple leads to controller

Teflon plug

Approximate level of coal

Spring clamps supporting reaction vessel

Vacuum flask

Thermocouples

Supporting bracket mounted on oven door

FIGURE -1. DETAILS OF REACTION VESSEL

oven constant when required. In this   the controller is set manually to the desired temperature, usually 40°C, and is maintained in this mode until the temperature in the reaction vessel is at the desired start temperature. Once this has been achieved, the gas flow through the reaction vessel is changed from nitrogen to oxygen. The controller is also switched from manual to adiabatic control as described above.

The controller's final task is to stop the oxidation experiment once the temperature of the coal has reached a preset limit. This is done to prevent damage to the oven and the reaction vessel. Power to the controller is interrupted, so that the heating element can no longer be energized, and a solenoid valve cuts the flow of oxygen to the reaction vessel.

EXPERIMENTAL PROCEDURE

For most of the experimental programme two adiabatic ovens were available for coal testing, these were used to run duplicate experiments.

Having selected a coal type for testing, a 400g sample was weighed to provide sufficient coal for testing and for analysis. Each reaction vessel was loaded with 130g, an additional 20g was required to produce a petrographic mount, and 50g for proximate and ultimate analyses.

The coal sample was pulverized to -72 BSS mesh, split, and placed in a vacuum drying oven at 105°C for 10 to 12 hours, under vacuum.

After drying, 130g of coal, sufficient to fill one reaction vessel, was weighed and placed in the first oven. The coal was simply "spooned" into the reaction vessel with no attempt made to pack the coal. During loading the reaction vessel was clamped to the oven door which was in turn supported on a simple stand. Excess coal was wiped away from the neck of the reaction vessel, and the teflon plug, with its pipes and thermocouples, carefully pushed into place. The inlet tube was never removed from the plug to ensure that it always reached the

same position in the reaction vessel. The plug was then held firmly in place by the brass retaining ring and springs.

The gas supply and exhaust were next connected to the reaction vessel by "Quickfit" connectors, and a flow of approximately 100ml/min of nitrogen established. A quick check for leaks was then made before the oven door was pushed into place.

Finally, the air blower was started and the controller set to manual mode. The temperature of the oven was held at 40°C, the usual starting temperature for all experiments, while the coal sample was purged with nitrogen until the temperature of the coal stabilized at 40°C. At this point, the second oven was loaded using the same technique.

The time required for loading the reaction vessel was approximately five minutes, during which time any pre-oxidation of the coal would be minimal. Thermal equilibrium between the coal and the oven could usually be achieved within 24 hours.

Once the coal reached the desired start temperature, the gas supply was changed from nitrogen to oxygen, and the controller switched from manual to adiabatic operation. Occasional checks were made to ensure the controller was functioning correctly and to establish the coal-oven temperature differential. It was found that the controllers gave excellent service and could maintain the coal-oven temperature differential to less than 0.5°C.

Finally, when the temperature of the coal exceeded 200°C, the power to the controller was off and a solenoid valve cut the supply of oxygen, thereby bringing the self-heating to a stop.

THE COALS AND THEIR COLLECTION

With a view to studying the effect of petrographic and chemical properties of coal on its propensity to spontaneous combustion, a large range of coals was collected from the major coal mining centres in Queensland. Coal
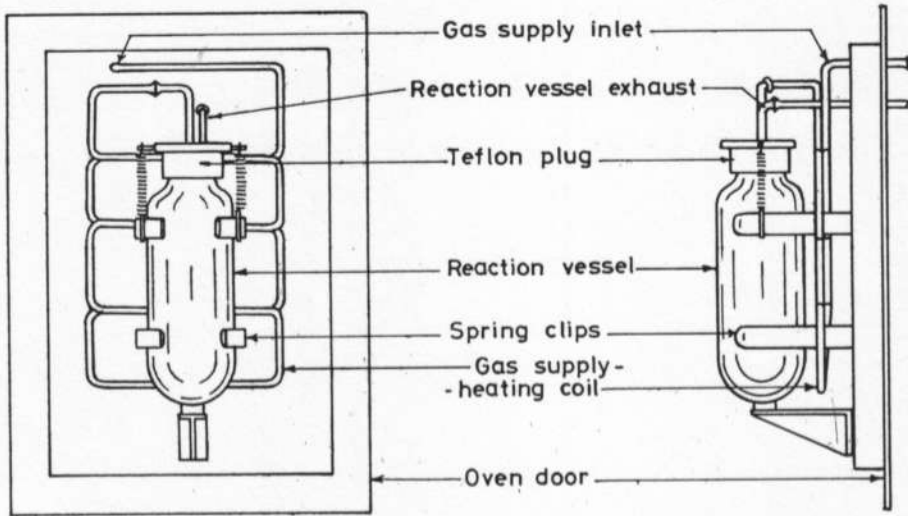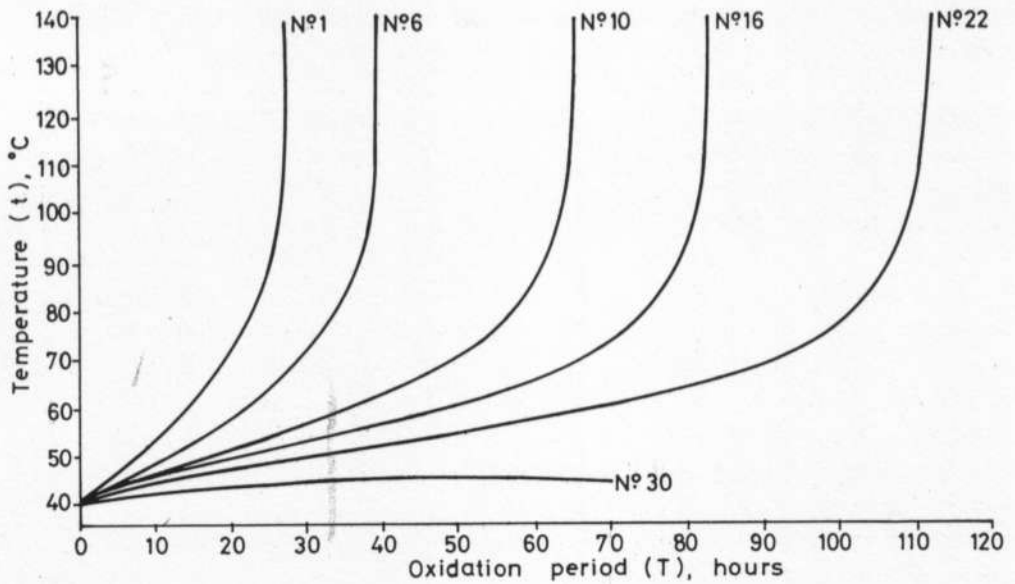
FIGURE-2. OVEN DOOR LAYOUT

FIGURE-4. SELF HEATING CURVES

samples were gathered from Ipswich, Moura, Blackwater and Collinsville (wherever possible from underground workings) as indicated in Figure 3. Table 1 lists the location, the mine & the seams sampled.

To increase the range of samples collected, a number of seams in each area was sampled and samples were taken from as many plies within the seam as possible.

Samples of coal, approximately one kilogram each, were sealed in a plastic bag, from which the air was expelled, and then placed in a large plastic drum. The drum was filled with water to exclude air and thereby reduce the possibility of pre-oxidation. It should be noted that previous attempts to store coal samples in nitrogen filled drums had not been successful.

EXPERIMENTAL RESULTS

In all, 94 tests were completed in this experimental programme, many being performed in duplicate when the second oven became available.

Many of the tests had to be repeated because the coal failed to produce a significant temperature rise, or because of power blackouts and equipment failures which brought tests to a premature end. As a result, the total number of coal samples successfully tested for their self-heating characteristics was reduced to 32.

Two other tests were performed on blends of coal and coal ash to determine the effect of the presence of mineral matter on the self-heating characteristics of coal.

For each coal tested, ultimate, proximate and petrographic analyses were determined. The chemical analyses were performed in the laboratory of the Department of Mining and Metallurgical Engineering, according to Australian Standards AS 1038, Part 6, 1971. The petrographic analyses were determined by the author, according to Australian Standard AS 2061.

THE FORM OF THE SELF-HEATING CURVE

For each coal tested, the temperature of the coal was continuously recorded on a chart recorder. From this information, a self-heating curve was drawn which was characteristic of that coal. Figure 4 illustrates the general form of self-heating curves for a selection of tests.

The self-heating curves for all the coals which produced a heating is characterised by a long, almost linear, first stage of heating which is followed by a very rapid increase in the rate of self-heating. The initial linear "incubation period" continues until the temperature rises to approximately $70^{\circ}C$. Above this point the rate of self-heating increases exponentially.

Many of the coals failed to produce a significant temperature rise, and as such represent a low spontaneous combustion propensity; Test No.30 (Figure 4) is typical of these coals.

The significant characteristic of the heating curves is the slope of the linear "incubation" section up to $70^{\circ}C$. It was thus decided to use this factor to denote the self heating propensity of the coal; designated R_{70} and defined as "the average self heating rate up $70^{\circ}C$". Clearly, as R_{70} increases, the propensity to spontaneous combustion increases.

THE EFFECT OF MINERAL MATTER

Despite the fact that mineral matter is present in all coals in widely varying proportions, its effect upon the propensity of coal to spontaneous combustion has received little attention. As the ash contents of Queensland coals are commonly 10% and more, it was decided that this was of some importance. Some of the coals tested for their self-heating characteristics had ash contents of up to 40%.

Consider a coal for which the ash content has been determined by proximate analysis, and assume that the mineral matter present in the coal does not oxidize (or otherwise react) to produce heat then,

Table 1

The coals under study

Location	Mine	Seam
Bundamba (Ipswich)	Blackheath O/C	Bluff Tops
		Bluff
	Box Flat No. 8 U/G	Bergin
	Normanton O/C	Rosewood No. 1
Moura	Moura No. 1 U/G	C
	Moura No. 2 U/G	D
Blackwater	Leichhardt U/G	Gemini
	Cook U/G	Castor
	Thiess South Blackwater U/G	C
Collinsville	CCCP No. 2 U/G	Bowen
	CCCP No. 3 U/G	Bowen
	CCCP No. 5 U/G	Blake

Table 2

The effect of ash content

Original sample taken from Rosewood No. 1 seam at Normanton Open Cut, Rosewood.

Original ash content: 9.00%

Test Description	Original Sample	+20% Mineral Matter	+40% Mineral Matter
Ash content	9.00%	9.00%+ 20%MM	9.00%+ 40%MM
Mineral matter	9.9%	29.9%	49.9%
Corr^N for M.M.	1.085	1.328	1.766
Average rate of heating to 70°C	1.375	1.098	0.7670
Corrected heating rate	1.492	1.458	1.354

Table 3

Self heating relative to brightness and analysis

Test No.	CP% D.M.M.F.	HP% D.M.M.F.	SP% D.M.M.F.	NP% D.M.M.F.	OP% D.M.M.F.	VP% D.M.M.F.	ASH%	VIT%	R_{70} °C/hr	R_{70A} °C/hr
1	82.5	5.5	0.29	1.36	10.35	37.4	13.9	92.8	1.45	1.66
2	81.9	5.3	0.37	1.27	11.16	34.0	37.1	68.6	1.00	1.56
3	79.9	6.3	0.37	1.55	11.88	48.5	9.0	100.0	1.35	1.47
4	82.9	5.3	0.29	1.63	9.88	35.6	14.6	82.0	1.07	1.24
5	82.5	5.7	0.37	1.41	10.02	36.0	37.6	83.8	0.79	1.24
6	82.2	5.3	0.34	1.39	10.77	36.5	15.5	87.7	0.98	1.14
7	83.3	5.3	0.29	1.56	9.55	36.2	7.2	76.7	0.94	1.01
8	83.0	5.3	0.31	1.57	9.82	35.3	12.7	70.8	0.88	1.00
9	80.6	7.0	0.67	1.39	10.34	56.5	17.4	100.0	0.76	0.90
10	85.6	5.1	0.41	2.14	6.72	28.6	6.1	75.1	0.60	0.64
11	85.0	4.9	0.27	1.39	8.44	29.6	17.8	60.3	0.52	0.63
12	84.3	5.2	0.38	2.22	7.90	32.9	4.7	53.0	0.58	0.61
13	84.4	5.7	0.33	1.70	7.87	36.7	27.8	85.1	0.43	0.58
14	85.1	5.1	0.37	2.05	7.38	29.5	7.3	65.6	0.52	0.56
15	85.4	5.2	0.38	2.02	7.00	28.8	6.1	63.8	0.45	0.48
16	85.0	4.8	0.45	2.04	7.71	26.6	7.4	67.7	0.44	0.47
17	87.2	4.8	0.63	1.60	5.77	25.6	11.1	67.9	0.41	0.46
18	85.2	5.1	0.37	2.01	7.42	28.3	12.1	33.0	0.37	0.42
19	86.4	5.0	0.35	1.92	6.33	25.5	6.8	68.3	0.38	0.41
20	85.3	5.1	0.38	2.13	7.09	29.2	6.0	66.8	0.38	0.40
21	85.9	5.3	0.53	1.83	6.44	31.2	11.0	70.5	0.32	0.36
22	85.7	5.1	0.41	2.13	6.65	29.4	6.1	60.4	0.33	0.35
23	86.3	4.9	0.39	1.91	6.50	24.9	6.9	67.3	0.31	0.33
24	85.5	5.0	0.45	2.12	6.93	28.7	6.3	35.0	0.29	0.31
25	86.2	5.3	0.63	1.67	6.20	32.3	6.3	87.3	0.28	0.30
26	87.3	4.6	0.27	1.88	5.95	20.8	8.2	7.3	0	0
27	88.7	4.6	0.30	1.93	4.47	21.6	5.1	20.6	0	0
28	86.9	4.3	1.41	1.77	5.62	21.3	9.8	17.5	0	0
29	87.6	4.7	0.54	2.07	5.09	24.4	16.6	24.6	0	0
30	89.1	4.4	0.68	1.89	3.93	20.2	9.7	18.6	0	0
31	88.9	4.6	0.98	1.80	3.72	20.0	7.7	4.4	0	0
32	88.0	4.4	0.69	1.71	5.20	18.6	19.3	19.5	0	0

if A = the ash content (%)

& r_o = the rate of heating of the ash-coal sample (^{o}C/hr)

and assuming that the amount of mineral matter present in the original sample is given by

MM $\div$ 1.1 x A (%),

then,

$$Q = \frac{r_o(MM \times Cp_m + (100 - MM) \times Cp_c)}{(100 - MM)}$$

$$= \frac{r_o(1.1 \times A \times Cp_m + (100-1.1xA) \times Cp_c)}{(100 - 1.1A)}$$

Where Q = the rate of heat production per unit weight of pure coal (cal/gm/hr)

Cp_m = the specific heat of mineral matter (cal/gm/^{o}C)

Cp_c = the specific heat of the pure coal (cal/gm/^{o}C)

If no ash was present in the coal sample, then the rate of heating of the pure coal sample would be:

$$r_c = \frac{Q}{Cp_c}$$

$$= \frac{r_o(1.1A \times Cp_m + (100-1.1A) \times Cp_c)}{(100 - 1.1A) \times Cp_c}$$

$$= r_o \frac{1.1A}{(100-1.1A)} \times \frac{Cp_m}{Cp_c} + 1$$

The term:

$$I = \frac{1.1 \times A \times Cp_m}{(100-1.1A) \times Cp_c} + 1$$

may be regarded as the correction to be applied to the observed rate of heating to determine the mineral-matter-free rate of heating.

Gomez, Gayle and Taylor (1965) have suggested that the specific heat of coal ash is approximately 0.20 cal/gm, while the specific heat of coal can be determined from:

Cpc = (0.189 x CP + 0.874 x MP + 0.491 x NP + 0.360 x OP + 0.215 x SP)/100 (cal/g/^{o}C)

Where CP = Carbon Content D.M.M.F. %

HP = Hydrogen Content D.M.M.F. %

NP = Nitrogen Content D.M.M.F. %

OP = Oxygen Content D.M.M.F. %

SP = Sulphur Content D.M.M.F. %

(These symbols are also used later in presenting the experimental data).

To test the validity of the correction determined above, a series of three tests was performed. The first determined the self-heating rate, R_{70}, of a run-of-mine coal sample (ash content 9%). To this coal was added 20% and 40% by weight mineral matter (ash obtained from the analytical laboratory) and the self-heating tests repeated on the coal-ash blends. The results of these tests are shown in Table 2. The correction applied to obtain the mineral matter free rate of self-heating, R_{70A}, appears to be valid, even though in the last test there was nearly 50% inert material in the blend.

Having determined the correction required for the presence of mineral matter, it is possible to consider the effects of coal composition upon its propensity to spontaneous combustion.

THE EFFECT OF RANK

It has long been recognized that the propensity of coal to spontaneous combustion is related to its rank. It is accepted that low rank coals represent a greater spontaneous combustion risk than high rank coals.

Coal rank is a measure of the degree of change which the origin plant material has undergone in its conversion to coal. During coalification, the physical and chemical properties of the coal alter as its nature approaches that of graphite.

In general, as the rank of coal increases, the carbon content increases while the oxygen, hydrogen and volatile contents decrease. If, in fact, propensity of coal to spontaneous combustion is influenced by rank, then it should be possible to relate the rates of self-heating to the chemical elements and components given above.

The chemical analyses of the coals tested in this programme are shown in Table 3. Also shown are the vitrinite contents along with the
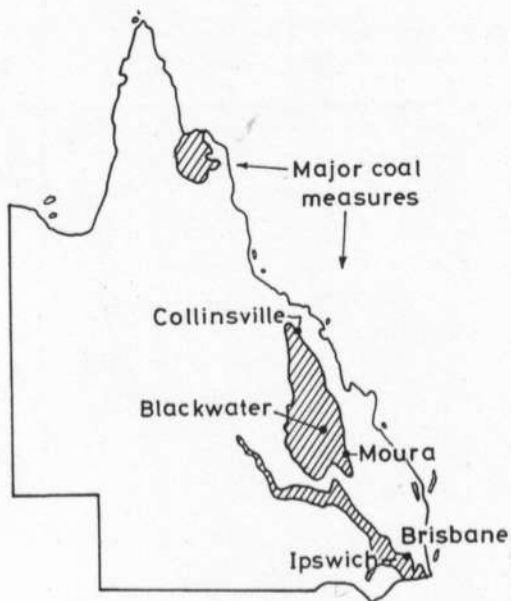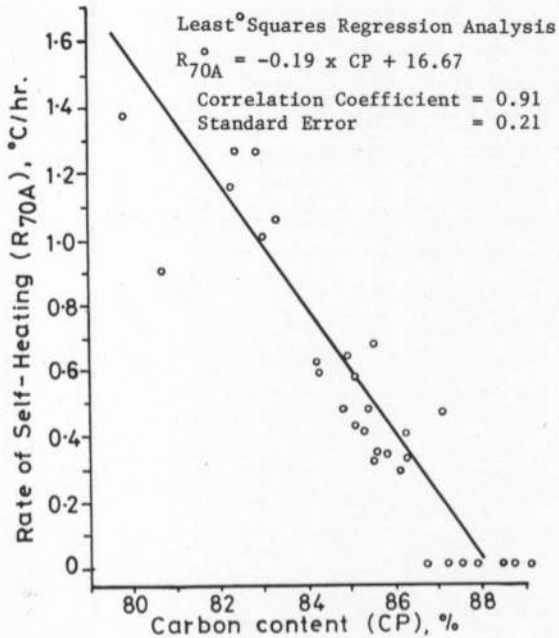
FIGURE-3
LOCATION OF COAL SAMPLES

Least Squares Regression Analysis

$R_{70A}^{\circ} = -0.19 \times CP + 16.67$

Correlation Coefficient = 0.91
Standard Error = 0.21

FIGURE -5
RATE OF SELF-HEATING
VS. CARBON CONTENT

Least Squares Regression Analysis

$R_{70A} = 0.21 \times OP - 1.01$

Correlation Coefficient = 0.94
Standard Error = 0.17
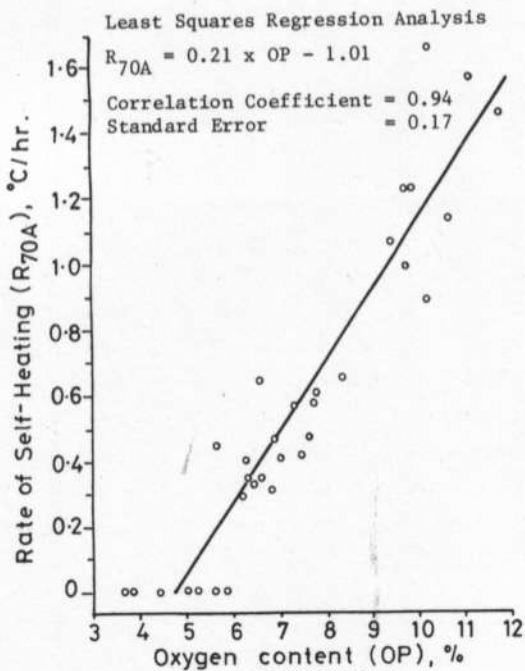
FIGURE - 6
RATE OF SELF HEATING
VS. OXYGEN CONTENT

Least Squares Regression Analysis

$R_{70A} = 0.014 \times VIT - 0.22$

Correlation Coefficient = 0.77
Standard Error = 0.31
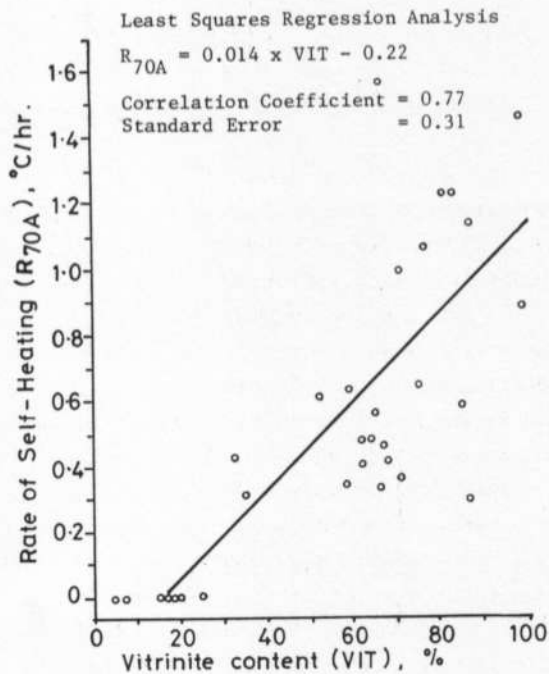
FIGURE -7
RATE OF SELF HEATING
VS. VITRINITE CONTENT

measured and corrected rates of self-heating
(R_{70A}). These data have been used to draw
Figures 5 and 6, which show the corrected rate
of self-heating plotted against the carbon and
oxygen contents of the coal.

In both cases, there is clearly a strong
correlation, indicating that the propensity to
spontaneous combustion increases with decreas-
ing rank. The straight line shown is the least
square regression line of best fit for which
the equation is also shown. The correlation
coefficients being 0.91 for carbon and 0.94
for oxygen.

The relationships between self heating
rate and the hydrogen and volatile contents are
not nearly as strong. The correlation
coefficient of self-heating rate with hydrogen
percent is only 0.68 and for volatiles percent-
age is 0.77.

Although nitrogen and sulphur have no
bearing upon the rank of a coal, and are usually
very minor constituents, it is convenient to
discuss their relationship to the propensity to
spontaneous combustion at this stage. Whilst
it has never been suggested that the occurrence
of spontaneous combustion is linked in any way
to the nitrogen content of coal, the effect of
sulphur has always caused some debate. It
was found that the correlation coefficient
between nitrogen and the rate of self-heating
was 0.65 and for sulphur the correlation
coefficient was 0.46.

From the data presented, it can be seen
that there is a strong relationship between
rank (as measured by carbon and oxygen content)
and the propensity to spontaneous combustion.
While there is some scatter in the results,
there are few anomalies.

PETROGRAPHIC COMPOSITION (MACERALS)

The petrographic composition of coal is
completely independent of the rank of the coal
as it is determined by the nature of the
original vegetable material from which the coal
formed rather than the degree of coalification

that has occurred.

It is possible for a very wide range of
petrographic compositions of coal to occur at
any rank. The range of vitrinite contents
observed in coals tested in this programme was
from 4.4% to 100%. Figure 7 shows the corrected
rate of self-heating plotted against the coal
vitrinite content, and it can be seen that there
is a trend for increasing propensity to
spontaneous combustion with increasing vitrinite
content.

The correlation coefficient for the data is
0.77 and the line of best fit is also shown in
Figure 7.

Unfortunately, the vitrinite content of the
coals correlates fairly strongly with the coal
rank. The correlation coefficient between
carbon and vitrinite is 0.80 and between oxygen
and vitrinite is 0.77. This indicates that, for
the coals tested, the vitrinite content tends
to decrease as the coal rank increases. The
rate of self-heating is so strongly correlated
with the rank, it is possible that the correl-
ation obtained between petrographic composition
and propensity to spontaneous combustion is
due only to the selection of the coals tested.

To determine the effect of petrographic
composition on the propensity to spontaneous
combustion, it would be necessary to examine
the self-heating characteristics of coals of
the same rank but different petrographic
compositions. As the number of coals of similar
rank tested in this programme is limited, this
is not practicable. However, it is possible to
consider the effect of rank and petrographic
composition simultaneously to see if any
improvement of previous analyses can be made.

THE COMBINED EFFECTS OF COAL RANK AND PETRO-
GRAPHIC COMPOSITION

To examine the combined effects of coal rank
and petrographic composition, it was necessary
to use a multivariable linear regression
computer programme.

This programme allowed the regression of the

rate of self-heating against a number of variables and combinations of variables.

If the rate of self-heating is a function of rank and petrographic composition, then it is reasonable to assume that the rate of self-heating can be expressed in the form:

$$R_{70A} = fn_1(CP) \times fn_2(VIT) + k_o$$

$$\text{and } R_{70A} = Fn_1(OP) \times Fn_2(VIT) + k_o$$

where k_o, K_o are constants,

and VIT = the vitrinite content of the coal (%)

Further, it seems reasonable to assume that the rate of self-heating will be linear with rank; i.e. carbon and oxygen contents, and that this assumption could be extended to the effect of petrographic composition expressed as the vitrinite content.

Appropriately, the previous relationship can be modified to give:

$$R_{70A} = k_1(CP + k_2) \times (VIT + k_3) + k_o$$

$$\text{and } R_{70A} = K_1(OP + K_2) \times (VIT + K_3) + K_o$$

where k_o, k_1, k_2, k_3 are constants

and K_o, K_1, K_2, K_3 are constants.

Expansion of these equations and using a multivariable linear regression analysis allows the determination of the best fit equation for the available data. These were found to be:

$$R_{70A} = -(\frac{1}{4155}) \times (CP-96.9) \times (VIT+613)-1.34$$

Correlation Coefficient = 0.91

Standard Error = 0.21

$$\text{and } R_{70A} = (\frac{1}{1218})(OP-3.16) \times (VIT+166)-0.23$$

Correlation Coefficient = 0.95

Standard Error = 0.16

These results give very little improvement over the correlation coefficients when the rate of self-heating was regressed against carbon and oxygen contents alone. Further, as shown below, the above relationships tend to diminish the importance of petrographic composition on the rate of self-heating. Because of the order of the magnitude of the terms k_3 and K_3 (613

and 166 respectively), there is a relatively small change to be seen for a large change in the vitrinite content. Most of the variation in the propensity to spontaneous combustion, as indicated by these relationships, is due to changes in rank.

To test the validity of the assumption that both rank and petrographic composition affect the propensity to spontaneous combustion, a further regression analysis of the data was made in which the rate of self-heating was assumed to be directly proportional to the vitrinite content. The best fit equations for all the available data were found to be:

$$R_{70A} = -\frac{1}{600} \times VIT \times (CP - 90)$$

Correlation Coefficient = 0.89

Standard Error = 0.23

$$\text{and } R_{70A} = \frac{1}{466} \times VIT \times (OP - 4.04)$$

Correlation Coefficient = 0.93

Standard Error = 0.18

From this, it can be seen that, although the correlation coefficients are not the highest obtained for the data available, the relationships observed do show a fairly high level of agreement with the observed data. This is very encouraging as it indicates that the assumption that the rate of self-heating is directly proportional to the vitrinite content, is not wildly inaccurate. This would help to explain the anomalies observed in the straight rank ordering of coals and their propensities to spontaneous combustion.

On the other hand, however, there is no reason to accept that this is the final solution to the anomalies problem as the correlation coefficients determined are good, but less than those from previous single variable analyses. Clearly, further research and testing is required to determine which factors or combination of factors are the key to the propensity of coal to spontaneous combustion. It is unfortunate that, of the coals tested, there was a distinct variation of vitrinite

content with rank; high rank coals tended to be of low vitrinite content and low rank coals of high vitrinite content.

Future research and testing should be concentrated on coals which reverse this trend; i.e. low rank, low vitrinite coals and high rank, high vitrinite coals. Then it will be possible to determine whether petrographic composition does affect propensity to spontaneous combustion, or whether this is controlled only by the coal rank.

APPLICATION TO THE PRACTICAL SITUATION

In the analysis above, an attempt has been made to relate the propensity of coal to spontaneous combustion to the petrographic and ultimate analysis. While this was not wholly successful, the results of this research programme can be used as the basis for further research. The practical application of the knowledge obtained from laboratory investigations presents a complex problem and is a field which requires some comment.

Many factors which are likely to affect the propensity of coal to spontaneous combustion have been described and it can be seen that many factors, other than petrographic composition and rank, must be considered when applying data obtained under laboratory conditions to the practical situation. There is little or no control over the particle size of coal which may be left behind in the goaf. Little can be done to prevent pillar failures occurring and becoming potential sites for outbreaks of spontaneous combustion. Many of the factors that can be controlled in the laboratory can cause great problems when attempting to apply laboratory results to the mining situation.

It could be argued that the type of results obtained in this programme could at least be used as a relative index to the propensities of coal to spontaneous combustion. It could be expected that, if two coals had the same laboratory rate of self-heating, then similar

problems involving spontaneous combustion outbreaks could be expected. This, however, is not necessarily the case.

Consider, for example, the results obtained in tests Nos. 1, 5 and 6 and test Nos. 3 and 9. Both sets of coals were obtained from operating open cut mines. The coals used in test Nos. 1, 5 and 6 were obtained from the Blackheath Open Cut in Ipswich and the coals used in test Nos. 3 and 9 were obtained from the Normanton Open Cut at Rosewood. Both sets of coals had very high rates of self-heating (uncorrected for the presence of mineral matter) exceeding 0.75°C/hour, indicating a high propensity to spontaneous combustion. In the Blackheath Open Cut, there was ample evidence of fires resulting from spontaneous combustion. The smell of gobstink was intense and, in places, the seam could be seen to be burning. A thermocouple was placed at the site of one heating which was accessible and the temperature was found to exceed 600°C. In contrast, at the Normanton Open Cut, there was no evidence at all of spontaneous combustion and discussions with the manager revealed that there had been very few such instances.

The only major difference that could be observed between the two mines was in the nature of the overlying strata. The coal seam in the Blackheath Open Cut had overlying shaly strata, while at the Normanton Open Cut, the overlying strata was sandstone deposits. Perhaps, the difference between the two mines could be explained in terms of different thermal conductivity between the different types of overlying strata. The shaly deposits, with a strong cleavage parallel to the bedding planes, might have a lower thermal conductivity than the sandstone deposits and prevent effective dissipation of the heat produced by the oxidation of the coal.

Speculation on this subject is, however, beyond the scope of this paper, but only serves to illustrate the complexity of the spontaneous combustion process. Clearly, there is a need

for research on the application of laboratory results to the practical situation so that the occurrence of spontaneous combustion might be more accurately predicted.

CONCLUSION AND RECOMMENDATIONS FOR FUTURE RESEARCH

The spontaneous combustion of coal is a very complex and little understood phenomenon. Its occurrence in mines has been responsible for the loss of many lives and the cause of much damage to equipment. Occurrences of spontaneous combustion in stockpiles, or during transportation, may cause much damage, are difficult to control and detrimental to the quality of the coal.

The research programme has shown how the propensity of coal to spontaneous combustion might be related to its petrographic composition and rank. However, because of the choice of the coals tested, further research will be needed before this can be proven conclusively. In this programme, the coals tested, which were of low rank, were also generally of high vitrinite content. Conversely, the coals of high rank were also of low vitrinite content. It would be of great value to be able to investigate the self-heating characteristics of low rank, low vitrinite content and of high rank, high vitrinite content coals. There are ample coals fitting this description available in Queensland, such as the coal from the Callide district (carbon ca. 77%, vitrinite ca. 29%), the Blair Athol district (carbon ca. 81.4%, vitrinite ca. 35%), the Goonyella district (carbon ca. 88%, vitrinite ca. 60%) and the Peak Downs district (carbon ca. 88%, vitrinite ca. 70%).

Alternately, the effect of petrographic composition might be better understood if a series of samples could be taken down the face of a seam so that a wide variety of petrographic compositions could be obtained at the same rank of coal. This would require a great deal of sampling skill and would involve a large number

of samples for each seam, due to the thickness of Queensland seams.

An attempt was made to do this in this programme, by taking samples at regular intervals down each seam visited, but the sampling technique was rough at best.

It has been suggested above that the rate of self-heating of a coal is a function of the vitrinite content and of the position of the coal in the coalification series; i.e. its rank. In the past, the rank of a coal was defined in terms of the carbon content and the hydrogen content. Recently, however, it has been indicated that the reflectance of vitrinite is a much better index of rank (Stach, 1975 and Falcon, 1978) especially in the range of bituminous coals (carbon content 80-88%). From the reflectance of vitrinite, it is also possible to determine the elemental composition of the vitrinite (van Krevelen, 1957). It seems likely, therefore, that the propensity of coals to spontaneous combustion may be better related to the vitrinite reflectance, than to the coals' ultimate composition.

Finally, an investigation into the application of laboratory results to the practical situation should be made. The difficulties that this involves have already been indicated and represent the greatest obstacle to be overcome in the understanding of the phenomenon of spontaneous combustion.

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REFERENCES

Falcon, R.M.S., 1978. Coal in South Africa Part 11. The application of petrography to the characterization of coal. Mineral Sci. Engng. 10, 28.

Gomez, M., Gayle, J.B., Taylor, A.R., 1965. Heat content and specific heat of coals and related products. United States Bureau of Mines, Report of Information No. 6607.

Stach, E., et. al., 1957. Coal Petrology. Gebruder Borntraeger, Berlin.

Van Krevelen, D.W., & Schuyer, J., 1957. Coal Science. Aspects of coal constitution. (Elsevier : London).

DISCUSSION

A.J. HARGRAVES (B.H.P. Steel Division Collieries): What granulometry was used in the experiments and why? In view of what was stated about the minimum temperature for spontaneous combustion to occur why was 40 degrees Celsius used as the lower starting point.

D.R. HUMPHREYS (Australian Coal Industry Research Laboratories Limited): The particle size used was -72 mesh, the reason for that was that in the literature survey made before starting experimentation, it was found that decreasing the particle size increased the rate of oxidation. Apparently below about -72 mesh the maximum rate of oxidation has been reached and that is why -72 mesh was selected. $40^{o}C$ was taken as a starting temperature because it is approaching the ambient temperatures found in a coal mine. But it is higher than would be expected in a coal mine and perhaps it is open for looking at further, trying to start these experiments from lower temperatures. This appears to have been the problem with a lot of past research before, that the starting temperature for adiabatic experiments has been up very high, starting as high as 60 or 70 degrees C.

J. CARVER (H.M. Chief Inspector, U.K., (Retired)): The most important part of this paper relates to the application of research to practical conditions. The authors should follow it through in spite of the difficulties. For instance two mines were mentioned and what is of significance is why is one more liable to spontaneous combustion than the other. Is it because they are more negligent for instance in the one mine in their attitude towards spontaneous combustion than they are in the other? What is the minimum incubation time for a given coal under certain conditions? To answer this question may well mean a review of all case histories so that out of that mass of information some general guidelines can be formed for managers in mines. In the U.K. they have had to settle on a three months incubation period in which time, when that face finishes, the equipment has to be withdrawn and the area sealed off. If this is not done before the end of three months, there is trouble. It has been stated what trouble that can be, so what possibility is there of following through on this research so as to be of practical value to mining men?

Perhaps Professor Isobe might care to think about this too, what research is possible to identify, by means of instrumentation and monitoring, these hot spots? For a manager to know that a hot spot was developing might allow him to do something about it whereas now there is only CO monitoring to rely on; if there was another aid it might be helpful.

D.R. HUMPHREYS: Returning to the example given on the two open pits visited for collecting coal samples. The basic difference between the two open pits was that the sediments in the overlying strata were different, there were shaley type deposits in the Ipswich areas and more sandstone type deposits in the Rosewood area. There has been no chance to investigate it much further, possibly there is some thermal conductivity effect that comes into this with the cleavage planes that are in the shaley bands. The Ipswich area has been pretty thoroughly worked one way and the other and with the pre-working of hand mined areas, and with the open pits encroaching on old workings it is quite possible that the porosity of the sediments and the coal has been increased and may in actual fact be increaseing the rate at which oxygen can get into the coal seam. Yes there are moves afoot within A.C.I.R.L. to continue with the research on propensity of coal to spontaneous combustion and Mr. Cudmore could confirm this.

There is a current submission in for a grant to attempt to examine laboratory studies and try to project them into the field for the managers.

J. CUDMORE (Australian Coal Industry Research Laboratories Limited): One of the questions was related to how a mine manager might detect whether there was a hot spot present or not in an underground location. In the past A.C.I.R.L. has installed long thermocouples into goaf areas and has measured actual temperatures in the goaf. Goaf pipes have also been installed in the late 1950's to measure not only temperatures but also the composition of gases inside the goaf area. It was demonstrated that the use of these pipes enhanced the value of mine gas analysis and the $CO:O_2$ ratio as an indication of spontaneous combustion. Many years ago people attempted to use mercaptans - those terrible smelling compounds - which were intentionally left in the goaf area. If a heating developed they started to decompose and the stink gave clear indication to all of the presence of a heating. This is not a recommended procedure nowadays because there are well developed and proven methods for sampling and analysis of mine gases. Also worth mention is that A.C.I.R.L. is co-operating with the National Coal Board in commissioning and evaluating the Corex tube bundle system in a Queensland coal mine. No doubt more will be heard about this project at a later stage of the Symposium.

T. CALLCOTT (B.H.P. Central Research Lab.): In Table 3 there are some things that are interesting: first, sample 9 has an extremely high hydrogen content of 7% and an abnormally high volatile matter of 56.5% which must make it one of the most unusual coals in Queensland, and 100% vitrinite. It is a bit low on the reaction rate as can be seen from the graph over the page. Sample 1 also merits some

attention as an interesting coal. The specific coals and the very interesting data that have been collected, are meant to be looked at in some detail. In following through on that, the analysis should be changed a bit from what it is. Apparently the oxygen in these results is by difference and therefore is a less reliable result than the carbon; but the carbon plus oxygen adds to about 93 per cent so the two graphs are almost identical. Changing from one of the equations to the other by substituting for carbon or 93 minus oxygen the other way round, almost the right relationship that would be expected is obtained. Oxygen appears to be the right measure that should be used and judged in this study, and every time a test is finished the oxygen content of the residue material should be determined because that would reveal a lot about how much heating has occurred. None of the subsequent statistical analysis (i.e., multiple regression) with the use of the vitrinite appear to be valid because intercorrelations seem to exist. Possibly the regression should not be in the paper.

C.C. MUMBY (Anglo American Corporation of South Africa Ltd.): Is not the reason that a very close correlation was not obtained between laboratory analysis and the two pits used as examples that the sample has been reduced to an unnatural form. It is hardly likely to find the same for -72 mesh in the open cut. Is there not some physical characteristic in the two coals which could possibly be giving this spontaneous combustion in the one and not in the other and that the one is subject to degradation far greater than the other and something like that sort?

D.R. HUMPHREYS: It is quite possible. This was a laboratory study and a start had to be made somewhere. -72 mesh was selected as the particle size to give a maximum rate of oxidation. Also the samples that were taken from the two

collieries were spot samples so there is no
guarantee that those actual spot samples typifi-
ed a whole seam. Possibly in the Rosewood open
cut just the band was chosen that is the most
reactive and possibly in the Ipswich open cuts
just the band which is least reactive was chosen
so that as a whole the two seams may be quite
different. Spot samples were taken and it does
obviously leave it open to that sort of problem.
In this case the attempt was to look at the
individual spot samples and correlate their
characteristics rather than whole seams.

T. ISOBE (Hokkaido University, Japan):
Spontaneous combustion underground will occur
at the fresh surface such as near the fault
or the starting point of faces and remaining
pillars in the goaf. It has occurred just after
the cleavage generated and after the passage of
some time the cleavage surface will be dead and
have lost its activity. The activity of this
clean surface has a very very small duration.
On the problem of spontaneous combustion,
expecially on the starting condition this
problem cannot be neglected. Is there agree-
ment on this?

D.R. HUMPHREYS: There are a series of stages
that a coal will go through. There are diff-
erent reaction velocities in its life. A fresh
sample of coal will have a much higher oxidation
period, oxidation rate, and that will fall very
rapidly with time. In isothermal tests
research workers have shown that the rate of
oxidation drops very rapidly with the exposure
time or accumulated oxygen, but that it does
have some finite level that lasts for quite a
while.

W. ROBERTSON (Corex Laboratories, U.K.): The
comment from Mr. Mumby from South Africa about
why one cannot correlate laboratory test results
with what happens underground deserves support.
The reason is that the tests and all tests
carried out in a laboratory for spontaneous
combustion research are based on a carefully
prepared homogeneous sample - not necessarily
as far as size is concerned, but certainly as
far as chemical properties and petrographic
properties are concerned. The tests are carried
out on a homogeneous sample. In fact it is
prepared that way. But that isn't the situation
underground because coal is a very heterogenous
substance and it must be remembered that under-
ground some degradation occurs. One gets fine
coal and fine fusain in the cleat, there is an
irregular distribution of pyrites in various
forms. There is an irregular diffusion of air
particularly in the goaf; there is no real
control of temperature and all these things
contribute in one way or another to the cause
of spontaneous combustion. A good philosophy
about spontaneous combustion is that a good
mining engineer can set any coal on fire under-
ground, in many cases, without trying very hard.
Mr. Carver referred to the detection of
spontaneous combustion by heat sensing. This
is an old idea, of burying thermistors, thermo-
couples and similar devices in the gob, but
in order for these techniques to be successful
it requires pre-knowledge of where spontaneous
combustion is likely to occur. The reason is
that the strata are such a good insulator, unless
the sensing device is located to be very near
the source of the heat then one cannot really
measure any significant changes in temperature.
There is a development at the moment which is
being watched closely in the U.K. and this is
the use of an infrared thermal imaging device
which is capable of picking up very very small
changes in temperature and very small levels
of infrared radiation. It is a marvellous
device for identifying overheated rollers, over-
heated bearings, overheated contacts in gate
end boxes and things like that, but there has
not yet been enough experience as to its
validity or its use for detecting hot spots
or localised spontaneous combustion right to

the goaf.

D.R. HUMPHREYS: There is also another monitor being used on a regular basis in one of the Queensland pits on depillaring work. This is for picking up hot spots as they are retreating.

W. ROBERTSON: Is it within the goaf?

D.R. HUMPHREYS: It is certainly in depillaring areas. It is being used but how it is being applied is somewhat uncertain, but certainly there is ample scope for using infrared imaging. There are plenty of instruments available.

D. ROWLANDS (University of Queensland): The point is taken about trying to correlate laboratory work with that from the field, obviously that was not attempted. It was an attempt to get a feel for the kinds of coal that were available and the ranges of their incubation periods, bearing in mind that there was an explosion at Kianga where the management were using a six month incubation period when planning their workings. It is hoped to follow this work up, but it is really a problem of money and pairs of hands. Mr. David Humphreys will probably get involved with this in another research project. The next stage in this research will be to take a coal seam with a high propensity to spontaneous combustion and lithologically sample it from roof to floor.

The maceral content of each sample will then be determined together with its heating rate. Heating must start at some spot and intuitively it is felt that it most probably starts at an interface between two lithotypes. One lithotype may oxidise and heat more rapidly, white the other may have a lower ignition temperature. There is a range of conflicting evidence as to heating rates and ignition temperatures of lithologic bands of the same rank. There is still a lot of work to be done.

A.J. HARGRAVES: Bearing in mind that 25 years ago Dr. T. Wood was carrying out an apparently similar sort of research it would be appropriate to conclude on a note of "what's new?"

T. WOOD (University of Sydney): Spontaneous combustion like inflation is here to stay and there are always going to be lots of points of view on how to cure it. Certainly the problem is still there - how is it possible to simulate a fresh fall of broken coal in the laboratory? Perhaps it will never be possible. Possibly a distinction should be drawn between underground problems and the problems of transportation and storage. It seems the latter category is the one where there might be some hope of a laboratory test giving information about the storability and transportability of coal. But the transposition of the underground environment of spontaneous combustion to the laboratory is not at all sure.