

THEORETICAL AND EXPERIMENTAL RESEARCH ON OCCURRENCE
OF SPONTANEOUS COMBUSTION OF COAL SEAM

By

Toshiro ISOBE¹ and Kiyoshi HIGUCHI²ABSTRACT

Introducing the hypothesis that the cause of spontaneous combustion of coal is depending on the accumulation of heat produced by its oxidation, the authors derived the equation expressing the temperature change in a heap of fine coal. To solve the equation, thermal conductivity, specific heat and rate of heat generation of fine coal (-48 mesh) were measured at various temperatures in the range 20-65°C. The equation was solved numerically and the volume of fine coal which would ignite spontaneously was estimated as the function of ambient temperature. Using 170 Kg of fine coal, several experiments for confirmation were conducted. At the ambient temperatures of 60°C and 50°C, coal began to fire spontaneously about 60 and 110 hours later respectively.

In addition to this, the measured temperatures in the coal heap agreed with the calculated ones comparatively well. If more volume of fine coal were used, experimental generation of spontaneous combustion from a lower temperature should be possible also.

INTRODUCTION

Spontaneous combustion of coal takes

¹Professor, Dept. of Mining Engineering,
University of Hokkaido

²Assistant Professor, Dept. of Mining
Engineering, University of Hokkaido

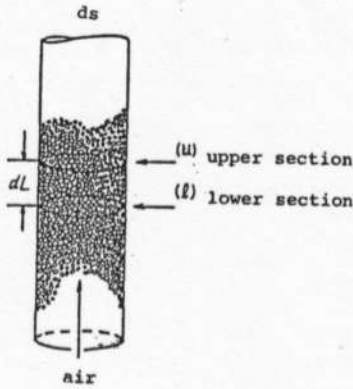
place at 30-40°C in practice. But the temperatures considered in previous investigations have been almost restricted to higher ranges. The purposes of this paper are:

- (1) Theoretical analysis, that is the mathematical expression of the spontaneous combustion process in a heap of fine coal.
- (2) Numerical calculation of the temperature change in the heap and the estimation of the volumes of fine coal which will ignite spontaneously from practical underground temperatures.
- (3) Experimental confirmation of the assumptions adopted by producing spontaneous combustion of coal not far from practical underground temperature. This study would help basic understanding of spontaneous combustion phenomena and play an important role in the development of the methods of prevention, early detection and arrest of spontaneous combustion of coal.

THEORETICAL APPROACH

The main cause of spontaneous combustion is considered to be the accumulation of heat in the coal heap and that the heat is generated by combination of coal substance and oxygen. Using the simplest model, (Fig. 1), thermal balance and oxygen balance in the heap of fine coal are investigated. In the following investigation, it is assumed that temperature

of coal particles and flowing air around them are same in the small element $dLdS$ considered.



- Temperature at the upper section: $T + \frac{\partial T}{\partial L} dL$ (°C)
- Temperature at the lower section: T (°C)
- Effective thermal conductivity of powdered coal: λ_e (cal · cm⁻¹ sec⁻¹ deg⁻¹)
- Specific heat of air: S_f (cal · g⁻¹ deg⁻¹)
- Density of air: ρ_f (g · cm⁻³)
- Specific heat of coal: S_c (cal · g⁻¹ deg⁻¹)
- Density of coal: ρ_c (g · cm⁻³)
- Flow rate of air: G (g sec⁻¹ cm⁻²)
- Porosity: ϵ

Fig1 One dimensional model of the heap of fine coal

Thermal Balance

In the one dimensional model as shown in Fig.1, total heat quantity Q (cal) accumulated in the small element $dLdS$, in a short time dt , can be expressed by equation(1).

$$Q = S_f \rho_f \epsilon dT dL dS + S_c \rho_c (1-\epsilon) dT dL dS \dots\dots\dots(1)$$

The heat flowing by thermal conduction that puts into the element through the lower section (q_l) and gets out from it through the upper section (q_u) are written as equation(2) and (3) respectively.

$$q_l = -\lambda_e \frac{\partial T}{\partial L} dS dt \dots\dots\dots(2)$$

$$q_u = -\lambda_e \frac{\partial}{\partial L} \left(T + \frac{\partial T}{\partial L} dL \right) dS dt \dots\dots\dots(3)$$

The heat accumulation in the element can be described by $q_l - q_u$.

$$q_l - q_u = \lambda_e \frac{\partial^2 T}{\partial L^2} dL dS dt \dots\dots\dots(4)$$

Enthalpy of air flow at the lower section (q'_l) and at the upper section (q'_u) are written as equation(5) and (6), respectively.

$$q'_l = S_f G T dS dt \dots\dots\dots(5)$$

$$q'_u = S_f G \left(T + \frac{\partial T}{\partial L} dL \right) dS dt \dots\dots\dots(6)$$

The heat accumulation in the element can be described by $q'_l - q'_u$.

$$q'_l - q'_u = -S_f G \frac{\partial T}{\partial L} dL dS dt \dots\dots\dots(7)$$

The heat generated in the element by the combination of coal particles with oxygen (q''') can be described by equation(8)

$$q''' = r' \Delta H dL dS dt \dots\dots\dots(8)$$

- where, r' : Apparent reaction velocity per unit volume of coal heap (mol sec⁻¹ cm³)
- ΔH : Apparent heat of reaction (cal mol⁻¹)

The total heat (Q) expressed by equation(1) should be equal to the sum of the heat accumulation by thermal conduction (Eq. (4)), by the enthalpy (Eq. (7)) and by the heat generated in the element (Eq. (8)). From the combination of these four equations equation(9) can be derived.

$$\frac{\partial T}{\partial t} [S_f \rho_f \epsilon + S_c \rho_c (1-\epsilon)] = \lambda_e \frac{\partial^2 T}{\partial L^2} - S_f G \frac{\partial T}{\partial L} + r' \Delta H \dots\dots\dots(9)$$

The equation can be simplified to equation(11) by substituting equation(10).

$$S_f \rho_f \epsilon + S_c \rho_c (1-\epsilon) = S_m \rho_m \dots\dots\dots(10)$$

$$S_m \rho_m \frac{\partial T}{\partial t} = \lambda_e \frac{\partial^2 T}{\partial L^2} - S_f G \frac{\partial T}{\partial L} + r' \Delta H \dots\dots\dots(11)$$

Conclusively, this equation is considered to be the basic equation which describes the heat balance in the heap of fine coal concerning the one dimensional model. Same procedure brings about equation (12) considered to the general three dimensional model.

$$S_m \rho_m \frac{\partial T}{\partial t} = \text{div}(\lambda_e \text{grad} T) - \text{div}(S_f G T) + r' \Delta H \dots\dots\dots(12)$$

Oxygen Balance

Substituting the temperature(T) with the oxygen concentration(C), same derivation as shown above leads to equation(13), that is the equation of oxygen balance.

$$\frac{\partial C}{\partial t} = \frac{D_e}{G/\rho_f} \frac{\partial}{\partial L} \left[\frac{\partial (GC/\rho_f)}{\partial L} \right] - \frac{G}{\rho_f} \frac{\partial C}{\partial L} - r' \dots\dots\dots(13)$$

where, D_e : Effective diffusion coefficient ($\text{cm}^2 \text{sec}^{-1}$)

C: Oxygen concentration (mol cm^{-3})

Relating to the three dimensional model, equation(14) is applicable.

$$\frac{\partial C}{\partial t} = \text{div} \left(\frac{D_e}{G/\rho_f} \text{grad} \frac{GC}{\rho_f} \right) - \text{div} \frac{GC}{\rho_f} - r' \dots\dots\dots(14)$$

In this equation, the first term of right members denotes oxygen consumption by diffusion, the second and the third terms denote the consumption by flow and the consumption by reaction respectively.

Apparent reaction velocity (r')

There are many reports¹⁾⁻⁶⁾ stating that the apparent reaction velocity of the reaction between fine coal and oxygen in the air can be closely expressed by Arrhenius' formula (Eq. (15)).

$$r' = A_a e^{-\frac{E_a}{RT}} \dots\dots\dots(15)$$

where, A_a : Apparent frequency factor ($\text{mol cm}^{-3} \text{sec}^{-1}$)

E_a : Apparent activation energy (cal mol^{-1})

R: Gas constant ($1.98 \text{ cal deg}^{-1} \text{ mol}^{-1}$)

T: Absolute temperature (K°)

Simplification of the equations

As derived above, general equations describing the heat accumulation process in the heap of fine coal are the

thermal balance equation(12), the oxygen balance equation (14) and the reaction velocity equation(15). By solving these equations simultaneously under the appropriate boundary and initial conditions, the heating process in the heap of fine coal could be obtained. Even though using the electronic computer, the solving work needs a lot of time,

And furthermore a lot of experimental works are necessary to obtain the values of many unknown constants. Therefore some simplifications of these equations must be considered. At first, in order to simplify equation(12), the heat transportation by air flow is considered to be ignored. This simplification should be reasonable because spontaneous combustion usually occurs underground where there is small amount of air leakage, and because small amount of air flow is thought to be enough to extend spontaneous combustion especially at low temperature range. In such a case equation(12) becomes to equation(16)

$$S_m \rho_m \frac{\partial T}{\partial t} = \text{div}(\lambda_e \text{grad} T) + r' \Delta H \dots\dots\dots(16)$$

In addition to this simplification, based upon the hypothesis that the oxygen consumption in the coal heap is not so much at low temperature range, the lowering of oxygen concentration in the heap of fine coal can be ignored. In this case, oxygen concentration is considered to be unchanged throughout the coal heap and the whole oxygen balance equation(14) can be ignored.

The simplest equation and constants necessary to solve the differential equation

By substituting equation(15) into the simplified equation(16) and using $A_a \Delta H = A (\text{cal cm}^{-3} \text{sec}^{-1})$, the simplest

equation describing heating process in the heap of fine coal may be written by equation(17).

$$S_m \rho_m \frac{\partial T}{\partial t} = \text{div}(\lambda_e \text{grad} T) + A e^{-\frac{E_a}{RT}} \dots (17)$$

To solve the equation and to make out the heating process in the heap of fine coal, volumetric specific heat ($S_m \rho_m$), effective thermal conductivity (λ_e), the constant (A) and apparent activation energy of the reaction are needed by all means

MEASUREMENT OF THE CONSTANTS

To know the above mentioned four constants of fine coal heaps, following experiments were conducted. Experimental apparatus is shown schematically in Fig. 2.

Coal samples

Three coal samples were obtained from the working faces of different coal mines and pulverized to smaller than 48 mesh. Table 1 shows the results of proximate analysis of these samples and the different treatments of these samples are shown in table 2.

Approximately 3.0Kg of pulverized coal sample is filled into the cylinder and tightened by a vibrator as shown in Fig.2.

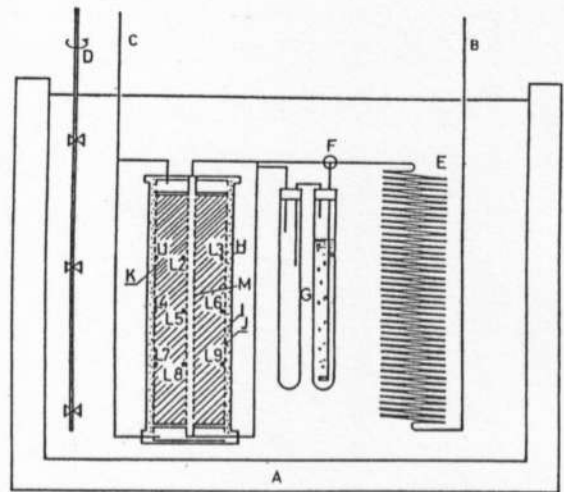
Table 1. Technical analysis (percent)

Sample	Moisture	Ash	Volatile Matter	Fixed Carbon	Sulphur *
Joban	7.4	16.7	42.6	33.3	1.0
Taiheiyō	5.7	7.8	46.6	39.9	0.2
Ooyubari	0.9	3.6	36.7	58.8	0.2

* moisture free base

Table 2. Treatments of Coal Samples

Sample	Pulverization and Sifting	Drying of pulverized coal
Sample a	in purified nitrogen gas.	in purified nitrogen gas at the temperature of 105°C for 48 hours.
Sample b	in the air	in purified nitrogen gas at the temperature of 105°C for 48 hours.
Sample c	in the air	no drying



- A: thermostatic bath
- B: air inlet
- C: air outlet
- D: stirrer
- E: preheating copper pipe (4mmφ, 30m)
- F: three way cock
- G: humidifier
- H: cylinder of stainless steel (inside dia 110mmφ, height 600mm)
- I: aluminum powder (+20mesh)
- J: cylinder of perforated stainless steel plate (100 mmφ)
- K: powdered coal (-48 mesh)
- L: thermocouple (Cu-Co, 0.32 mmφ)
- M: vinyl chloride perforated pipe (13 mmφ)

Fig.2 Apparatus for the measurement of heat generation in powdered coal

Aluminium powder (I) filled between the cylinder (H) and the perforated cylinder (J) plays two roles, to keep the same temperature of outer surface of the pile of fine coal as that of the thermostatic bath (A)

and to flow air or nitrogen through the pile of fine coal.

Measurement of the effective thermal conductivity

Flowing nitrogen through the cylinder, an electric current is sent to nichrome wire wound on the vinyl chloride perforated pipe (M). After attainment of the thermal stationary state, the effective thermal conductivity of the fine coal can be obtained by following equation⁷⁾

$$\lambda_e = \frac{q}{2\pi(T_a - T_b)l} \ln \frac{b}{a} \dots \dots (18)$$

where, T_a : temperature of the inner surface of the cylindrical pile of fine coal

T_b : temperature of the outer surface of the cylindrical pile of fine coal

l : length of the cylindrical pile of fine coal

q : heat given by electric current to nichrome wire

a : inside diameter of the cylindrical pile of fine coal (13mm)

b : outside diameter of the cylindrical pile of fine coal (100mm)

In this measurement, values of $T_a - T_b$ at the positions of L2, L5 and L8 showed good agreement, therefore it was confirmed that the cylindrical pile of fine coal might be considered as the cylinder having infinite length and that nitrogen diffused uniformly through the fine coal pile. Results obtained are shown in Tables 3, 4 and 5.

Measurement of heat generation

When temperature of the whole cylindrical pile of fine coal become uniform at the temperature of the thermostat bath, nitrogen stream will be changed to air stream. In these experiments, dry nitrogen and/or air were used for

Table 3 Effective Thermal Conductivity of Sample a (cal·cm⁻¹·sec⁻¹·deg⁻¹)

Temperature	Joban
35 °C	2.4 × 10 ⁻⁴
60 °C	2.6 × 10 ⁻⁴
mean value	2.5 × 10 ⁻⁴

Table 4 Effective Thermal Conductivity of Sample b (cal·cm⁻¹·sec⁻¹·deg⁻¹)

Temperature	Joban	Taiheiyo	Ooyubari
20 °C	2.6 × 10 ⁻⁴	2.4 × 10 ⁻⁴	-
35 °C	2.3 × 10 ⁻⁴	2.4 × 10 ⁻⁴	2.4 × 10 ⁻⁴
50 °C	2.7 × 10 ⁻⁴	2.4 × 10 ⁻⁴	2.2 × 10 ⁻⁴
65 °C	2.7 × 10 ⁻⁴	2.4 × 10 ⁻⁴	2.3 × 10 ⁻⁴
mean value	2.6 × 10 ⁻⁴	2.4 × 10 ⁻⁴	2.3 × 10 ⁻⁴

Table 5 Effective Thermal Conductivity of Sample c (cal·cm⁻¹·sec⁻¹·deg⁻¹)

Temperature	Joban	Taiheiyo	Ooyubari
20 °C	-	-	-
35 °C	2.8 × 10 ⁻⁴	2.7 × 10 ⁻⁴	-
50 °C	3.1 × 10 ⁻⁴	2.7 × 10 ⁻⁴	2.6 × 10 ⁻⁴
65 °C	3.0 × 10 ⁻⁴	2.6 × 10 ⁻⁴	2.6 × 10 ⁻⁴
mean value	3.0 × 10 ⁻⁴	2.7 × 10 ⁻⁴	2.6 × 10 ⁻⁴

dried coal sample a and b, and wet nitrogen (75% relative humidity) and/or air were used for non-dried sample c using the humidifier (G) as shown in Fig.2.

Oxygen in the air reacts with fine coal and the temperature of the central part of the cylindrical pile of fine coal rises gradually. After several hours, it attains a stationary state, and then the temperature of the inner surface of the cylinder is recorded. Basic equation described at this stationary temperature can be derived from equation (17) for cylindrical co-ordinates as follows.

$$\lambda_e \left(\frac{\partial^2 T}{\partial r_e^2} + \frac{1}{r_e} \cdot \frac{\partial T}{\partial r_e} \right) + A e^{-\frac{E_a}{RT}} = 0 \dots \dots (19)$$

here, r_c : distance from the axis of the cylinder made of pulverized coal

At low temperature ranges like 20-60 °C, the temperature ascending of the inner

surface of the cylinder attains several degrees at most, therefore the linear approximation for the heat generation term is introduced.

$$Ae^{-\frac{E_a}{RT}} = Q_0 + R_0 T \dots (20)$$

Q_0, R_0 : Constants

This approximation makes it possible to obtain analytical solution for equation(19)and(20) as follows.

$$Q_0 + R_0 T = (Q_0 + R_0 T_0)$$

$$\frac{Y_1 \left(\sqrt{\frac{R_0}{\lambda_e}} a \right) J_1 \left(\sqrt{\frac{R_0}{\lambda_e}} r_c \right) - J_1 \left(\sqrt{\frac{R_0}{\lambda_e}} a \right) Y_1 \left(\sqrt{\frac{R_0}{\lambda_e}} r_c \right)}{Y_1 \left(\sqrt{\frac{R_0}{\lambda_e}} a \right) J_1 \left(\sqrt{\frac{R_0}{\lambda_e}} b \right) - J_1 \left(\sqrt{\frac{R_0}{\lambda_e}} a \right) Y_1 \left(\sqrt{\frac{R_0}{\lambda_e}} b \right)} \dots (21)$$

where, J_0, J_1, Y_0, Y_1 : Bessel functions

The temperature ascending measured at the inner surface of the cylinder and the calculated heat generation based upon equation(21) are shown as following tables.

Table 6 Temperature Rise at the Inner surface of the Cylinder (deg)

(Sample a)	
Temperature	Joban
35° C	1.8
60° C	6.5

Table 7 Heat Generation by Oxydation (cal·cm⁻³·sec⁻¹) (Sample a)

Temperature	Joban
35° C	70 × 10 ⁻⁶
65° C	250 × 10 ⁻⁶

Table 8 Temperature Rise at the Inner Surface of the Cylinder heat generation. In addition to this, the measured effective thermal conductivity values are approximately same as the values appearing in other reports¹⁰⁾ (11)12) on the thermal conductivity

(Sample b)		(deg)	
Temperature	Joban	Taiheiyo	Ooyubari
20°C	0.5	0.6	----
35°C	1.1	0.8	0.1
50°C	3.2	2.5	0.3
65°C	11.1	7.4	0.7

Table 9 Heat Generation by Oxydation (cal·cm⁻³·sec⁻¹) (Sample b)

Temperature	Joban	Taiheiyo	Ooyubari
20°C	19 × 10 ⁻⁶	23 × 10 ⁻⁶	-
35°C	43 × 10 ⁻⁶	31 × 10 ⁻⁶	50 × 10 ⁻⁷
50°C	13 × 10 ⁻⁵	91 × 10 ⁻⁶	10 × 10 ⁻⁶
65°C	37 × 10 ⁻⁵	26 × 10 ⁻⁵	26 × 10 ⁻⁶

Table 10 Temperature Rise at the Inner Surface of the Cylinder (deg)

(Sample c)			
Temperature	Joban	Taiheiyo	Ooyubari
20°C	-	-	-
35°C	0.8	0.5	-
50°C	1.0	0.9	0.2
65°C	1.7	2.4	0.5

Table 11 Heat Generation by Oxydation (cal·cm⁻³·sec⁻¹) (Sample c)

Temperature	Joban	Taiheiyo	Ooyubari
20°C	-	-	-
35°C	38 × 10 ⁻⁶	27 × 10 ⁻⁶	-
50°C	52 × 10 ⁻⁶	48 × 10 ⁻⁶	10 × 10 ⁻⁶
65°C	83 × 10 ⁻⁶	12 × 10 ⁻⁵	22 × 10 ⁻⁶

A few discussions on the results obtained

(a) It has been already known that the effective thermal conductivity of the pile of fine coal and the thermal conductivity of coal substance have higher values at high temperature range than those which are obtained at low temperature range when they have been observed wide temperature range like 0-1000°C (8)9). However, as shown in Tables 3,4 and 5, the effective thermal conductivity of fine coal cannot be seen as a function of temperature in the narrow temperature range as 20-65°C, therefore mean values were used for the calculation of the

of fine coal with no gas flow. This fact means that the effect of the flow of air and/or nitrogen on the heat flow is considerably small in this experiment.

(b) Relations between the ambient temperature and heat generation are shown in Fig.3. As being able to be seen from the figure, the reciprocals of the absolute ambient temperatures and the heat generations show fairly good linear correlations. Therefore it is clear that the relation between the ambient temperature and the heat generation can be expressed by Arrhenius' formula. Taking logarithms of both side of equation(22), and using the least squares methods, apparent activation energy (E_a) and constant (A) were determined as shown in Table 12.

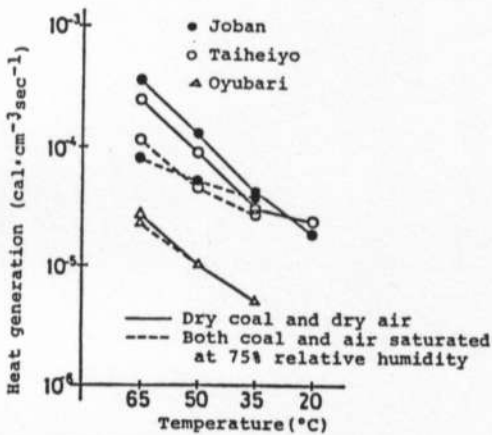


Fig.3 Heat generation in powdered coal

$$\text{Heat generation} = A \exp\left(-\frac{E_a}{RT}\right) \dots (22)$$

Table 12 Apparent Activation Energy (E_a) and Constant (A)

Treatment	Sample	E_a (Kcal·mol ⁻¹)	A (cal·cm ⁻³ sec ⁻¹)
Sample a	Joban	10.3	1.5×10^{-3}
	Joban	11.0	4.4×10^{-3}
	Taiheiyo	10.8	2.2×10^{-3}
Sample b	Ooyubari	11.0	4.0×10^{-3}
	Joban	5.5	2.4×10^{-3}
	Taiheiyo	10.3	6.0×10^{-3}
Sample C	Ooyubari	10.3	1.0×10^{-3}

NUMERICAL CALCULATION OF THE TEMPERATURE CHANGE IN THE HEAP OF FINE COAL AND ESTIMATION OF THE VOLUMES OF FINE COAL WHICH WILL IGNITE SPONTANEOUSLY

As derived before, temperature change in the heap of fine coal is described by equation(17). Therefore, whether spontaneous combustion occurs or not in a coal heap will be forecasted by the appearance of the hot spot whose temperature exceeds ignition temperature of coal, say 300°C or more. For the convenience of numerical calculation, spherical co-ordinates are adopted for the estimation of coal volumes which will ignite spontaneously. Equation(17) takes the form of equation(23) in this case.

$$S_m \rho_m \frac{\partial T}{\partial t} = \lambda_e \left(\frac{\partial^2 T}{\partial r^2} + \frac{2}{r} \frac{\partial T}{\partial r} \right) + A e^{-\frac{E_a}{RT}} \dots (23)$$

r: distance from the center of the sphere

It is too difficult to obtain analytical solutions of this equation owing to the Arrhenions' heat generation term, therefore the approximate difference equation(24) was solved numerically instead of equation(23)

$$T_{m,n+1} = T_{m,n} + k C_1 \left(\frac{T_{m-1,n} - 2T_{m,n} + T_{m+1,n}}{h^2} + \frac{2}{mh} \frac{T_{m+1,n} - T_{m,n}}{h} \right) + k C_2 \exp\left(\frac{-E_a}{RT_{m,n}}\right) \dots (24)$$

where, $C_1 = \frac{\lambda_e}{S_m \rho_m}$, $C_2 = \frac{A}{S_m \rho_m}$
 $T_{m,n} = T(mh, nk)$

h: small increment of distance

k: small increment of time

Boundary and initial conditions applied are as follows.

$$T(\text{surface}, t) = T(\text{surface}, 0) = T_0, \quad t > 0 \dots (25)$$

$$T = T_0, \quad t = 0 \dots (26)$$

T_0 : ambient temperature

Almost all of constants except volumetric specific heat of fine coal ($S_m \rho_m$) have been obtained and listed above.

As described in equation(10), $S_m \rho_m$ equals to $S_f \rho_f \epsilon + S_c \rho_c (1-\epsilon)$.

L.C.MCCABE and C.C. BOLEY¹³⁾ reported that specific heat of coal (S_c) lies between 0.2 and 0.4 ($\text{cal g}^{-1} \text{ } ^\circ\text{C}^{-1}$).

Density of coal (ρ_c) is known to be 1.2-1.5 (g cm^{-3}) by the measurement using water or helium. Specific heat of air (S_f) is 0.24 ($\text{cal g}^{-1} \text{ } ^\circ\text{C}^{-1}$) and density of air is approximately 1.2×10^{-3} (g cm^{-3}) whilst overlooking a little change with humidity. Table 13 shows calculated $S_m \rho_m$ as a function of porosity ϵ for Joban coal. As it can be seen from the table, the values of the volumetric specific heat of fine coal are expected to be 0.16-0.27 ($\text{cal g}^{-1} \text{ } ^\circ\text{C}^{-1}$). From this estimation, 0.23 ($\text{cal g}^{-1} \text{ } ^\circ\text{C}^{-1}$) corresponding porosity of 0.4 was used in the following calculations.

Table 13 Relation between Porosity(ϵ) and Specific Heat ($S_m \rho_m$)

ϵ	$1-\epsilon$	$S_m \rho_m$ ($\text{cal} \cdot \text{g}^{-1} \cdot \text{ } ^\circ\text{C}^{-1}$)
0.3	0.7	0.27
0.4	0.6	0.23
0.5	0.5	0.20
0.6	0.4	0.16

Several results of calculation

Under the hypothesis that required quantity of oxygen for reaction with fine coal is supplied from nowhere, Fig. 4 shows the possibility of self ignition of the spherical shaped pile of Joban fine coal from the ambient temperature of 40°C. Fig. 5 shows the relation between the quantity of the spherical shaped pile of fine coal and the temperature rise of the central part of the sphere. It can be seen from the figure that some amount of fine coal is neces-

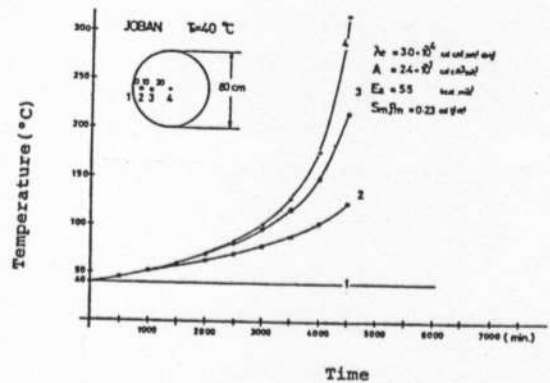


Fig. 4 Computed temperature-time curves

sary for the occurrence of spontaneous combustion from an ambient temperature, and that even though at very low ambient temperature, enough volume of fine coal may lead to spontaneous combustion. As a result of the repeat of same calculation for different coal samples, relations between ambient temperature and volume of fine coal which would ignite spontaneously were obtained as shown in Fig. 6. Three lines in the figure indicate the smallest volume of fine coal which may ignite spontaneously from the arbitrary ambient temperature.

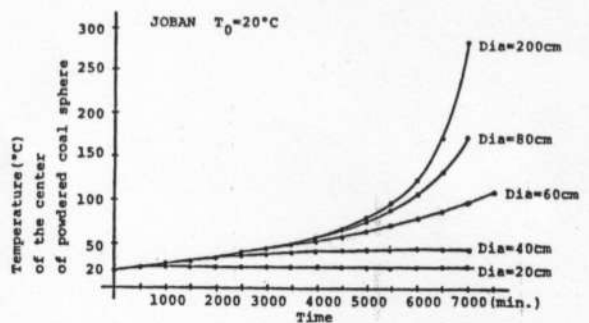


Fig. 5 Computed temperature-time curves for different diameter powdered coal sphere ($T_0=20^\circ\text{C}$)

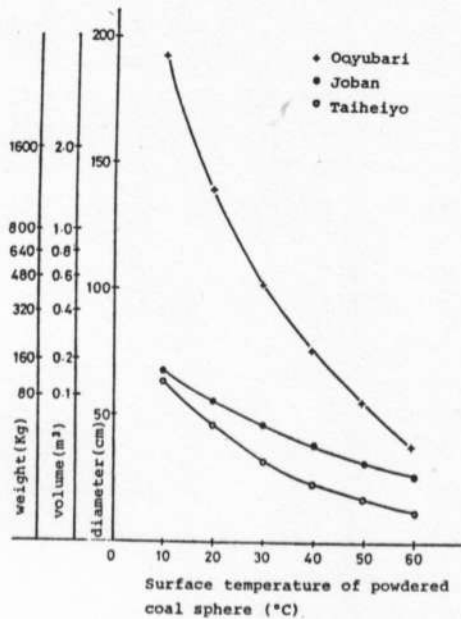
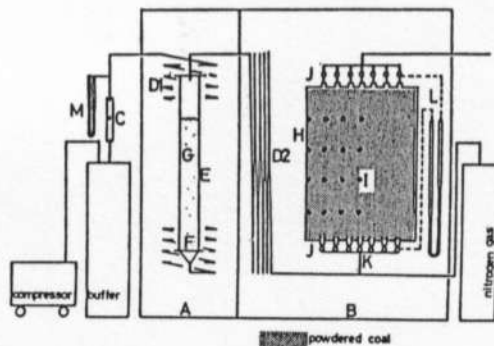


Fig.6 Relations between surface temperature of powdered coal sphere and volume of powdered coal which will ignite spontaneously

A FEW EXPERIMENTS ON SPONTANEOUS COMBUSTION OF FINE COAL



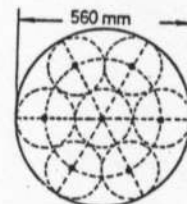
A,B: Thermostatic chamber
 C: Flowmeter
 D1,D2: Preheating copper pipe (10mm ϕ x 20m)
 E: Humidistat
 F: Glass filter
 G: Water
 H: Container of powdered coal (565mm x 870mm)
 I: thermocouple
 J: Needle regulator
 K: Junction
 L,M: Manometer

Fig.7 Equipment of spontaneous combustion

To ascertain the utility of the mathematical expression and the measured values obtained in this study, a few experiments were performed. The heap of fine coal investigated had a cylindrical form as shown in Fig.7 and its volume corresponded to about 170Kg of fine coal.

After making temperature difference between the thermostatic chamber A and B, air held water vapour corresponding to 90% relative humidity will be flowing into the container of fine coal.

To ascertain the uniform diffusion of the air throughout the pile of fine coal, seven air inlets and same number of outlets were installed as shown in Fig.8 and the structure of air inlet is shown in Fig.9. Fig.10 shows the positions of thermocouples to measure temperature change in the coal pile.



• Air Inlet
 Fig.8 Layout of Air Inlet

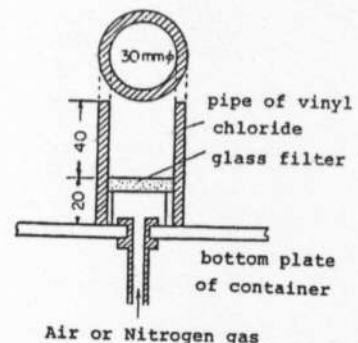


Fig.9 Structure of Air Inlet

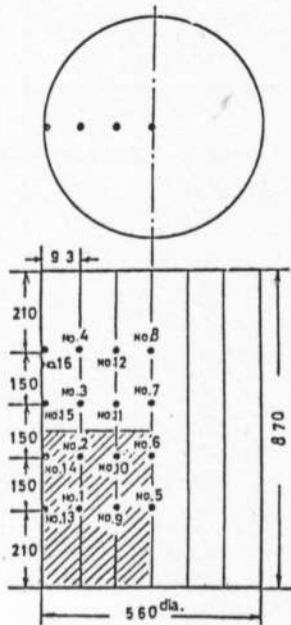


Fig.10 Positions of thermocouples in powdered coal

The initial and boundary conditions used for the experiment and calculation were same as that were used to solve the equation(25)and(26). To set up the initial condition experimentally,whole container of fine coal was filled with nitrogen and the temperature of the thermostatic chamber B was set at an ambient temperature. Temperature change in the heap of fine coal is described by equation (27)

$$S_m \rho_m \frac{\partial T}{\partial t} = \lambda \left(\frac{\partial^2 T}{\partial r^2} + \frac{1}{r} \frac{\partial T}{\partial r} + \frac{\partial^2 T}{\partial z^2} \right) \dots (27)$$

where, z: distance in the direction of the axis

It was considered that the effective thermal conductivity is homogeneous for all directions. Fig.11 shows computed and measured temperature changes in the container of fine coal as a function of $S_m \rho_m$. It can be seen from the figure that $S_m \rho_m$ is very close

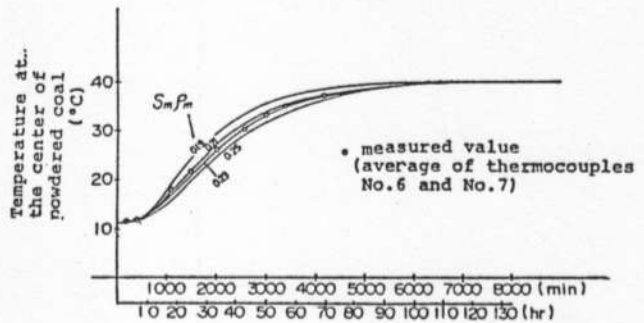


Fig.11 Computed and Measured Temperature in Powdered Coal Container which was filled with Nitrogen Gas

to 0.23 and that about six days are necessary to set up the initial condition, that means whole coal pile is in same temperature. As soon as the initial condition is established, it is commenced to flow air into the container of fine coal. Observing the oxygen concentration of outlet air flow, the quantity of air flow was regulated as precisely as possible. Heating process in the container of fine coal is described by equation (28).

$$S_m \rho_m \frac{\partial T}{\partial t} = \lambda \left(\frac{\partial^2 T}{\partial r^2} + \frac{1}{r} \frac{\partial T}{\partial r} + \frac{\partial^2 T}{\partial z^2} \right) + A e^{-\frac{E_a}{RT}} \dots (28)$$

Numerical solutions under the above mentioned conditions for the ambient temperatures of 60°C, 50°C, 40°C and 30°C and each experimental result corresponding each ambient temperature is shown in the following figures.

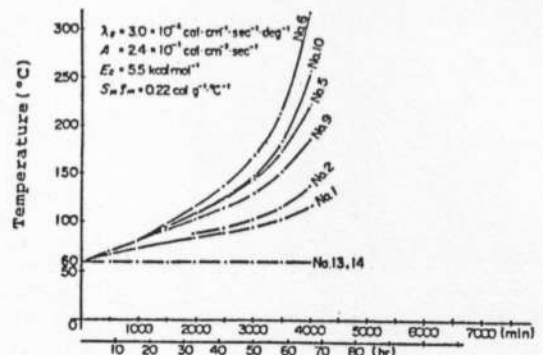


Fig.12 Computed Temperature - Time Curves (T₀ = 60°C)

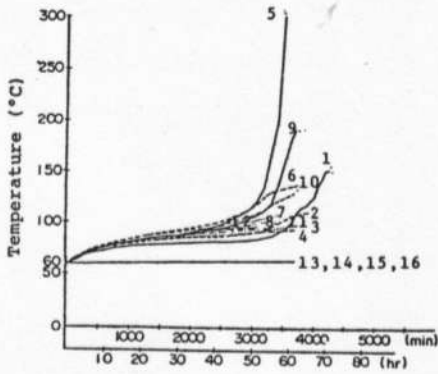


Fig.13 Experimental Result ($T_0=60^\circ\text{C}$)

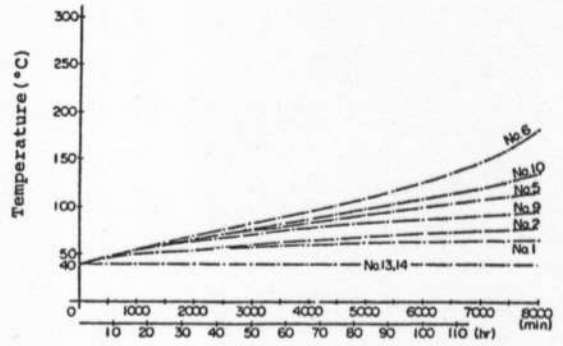


Fig.16 Computed Temperature - Time Curves ($T_0=40^\circ\text{C}$)

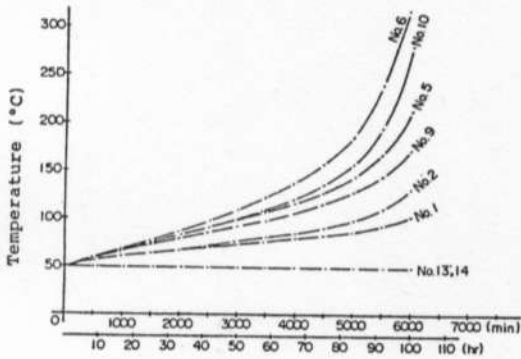


Fig.14 Computed Temperature - Time Curves ($T_0=50^\circ\text{C}$)

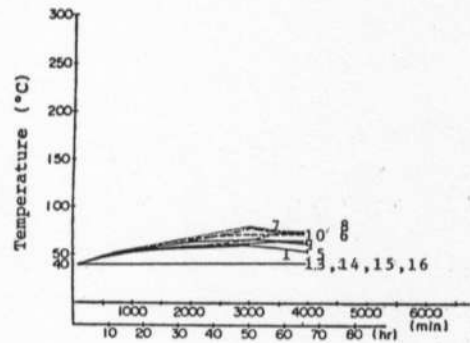


Fig.17 Experimental Result ($T_0=40^\circ\text{C}$)

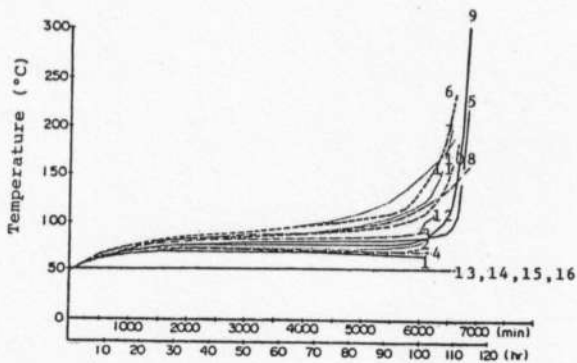


Fig.15 Experimental Result ($T_0=50^\circ\text{C}$)

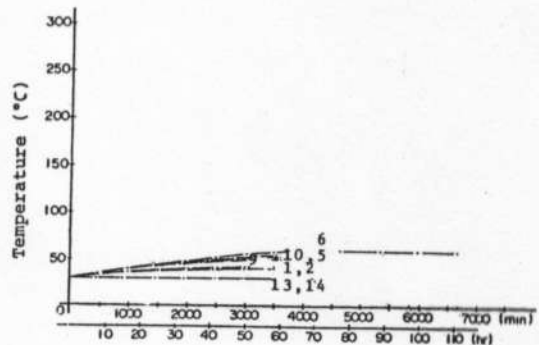


Fig.18 Computed Temperature - Time Curves ($T_0=30^\circ\text{C}$)

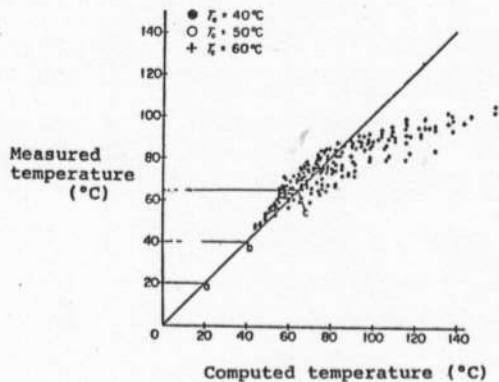


Fig.19 Comparison between Computed and Measured Temperatures

In the experiments at the ambient temperature of 60°C and 50°C, fine coal began to fire spontaneously within about 60 and 110 hours later respectively

In the case of the ambient temperature of 40°C, the maximum temperature in the container attained 81.4°C but the spontaneous combustion phenomenon was not obtained. Main reasons of this result were considered that the volume of fine coal used was so close to the minimum possible volume of spontaneous combustion that unconsidered factors like lowering of oxygen concentration of the air and disuniformity of the diffusion and so forth might play a hindering role on ignition.

Provided the temperatures below 80°C were concerned, the calculated temperatures and measured ones approximately agreed each other as being able to be seen in Fig.19.

The main causes of the disagreement of the calculated temperatures and measured ones above 80°C should be the endothermic effect of water evaporation from coal, the degradation of coal particles and the decrease of oxygen concentration in the air and so forth.

These factors were ignored in this study. If more volume of fine coal should be used, generation of spontaneous

combustion from lower temperature would be also possible experimentally, because at temperatures in the range of 20-65°C, thermal conductivity, specific heat and constants of the Arrhenius' formula remain without any changes,

CONCLUSION

- (1) The mathematical expression of spontaneous combustion process in the heap of fine coal was conducted.
- (2) To solve the simplified basic equation (17), necessary constants were obtained for three kinds of coal samples having a size of under 48 mesh.
- (3) Using spherical co-ordinates numerical calculations related with temperature change in the sphere of fine coal and the estimation of the volumes of fine coal which will ignite spontaneously from practical underground temperatures were conducted.
- (4) To confirm the utility of the mathematical expression and the constant values obtained in this study, experimental generation of spontaneous combustion were performed.
- (5) In the experiment using 170Kg of fine coal at the ambient temperature of 60°C, fine coal began to fire about 60 hours later from the commencement of air flow. At the ambient temperature of 50°C, it began to fire after about 110 hours later
- (6) Provided temperatures below 80°C were concerned, the calculated temperature changes and measured ones are well in agreement with each other.
- (7) If more volume of fine coal were used, experimental generation of spontaneous combustion from the lower temperatures should be also possible.

REFERENCES

- 1) W.PETERS;Gluckauf,101,1965,p.1526
- 2) P.HEUSINGER,H.MUNZNER;Brennstoff-Chemie,45,1964,p.357
- 3) J.LANGHOFF,W.PETERS;Erdol und Kohle 17.1964,p.900
- 4) H.MUNZNER,W.PETERS;Brennstoff-Chemie,46,1965,p.399
- 5) K.MATSUMOTO,S.NAKAMURA;J.Mining of Hokkaido,13,1957,p.201
- 6) C.KROGER;Brennstoff-Chemie,43,1962,p.328
- 7) S.YOKOBORI,O.KUGA;Basic thermal conduction Engineering,Maruzen,1967 pp.34-36
- 8) D.J.MILLARD;J.Inst.Fuel,28,1955,p.345
- 9) Y.SEKIMOTO,Dr.thesis,p44
- 10) T.YANAGIMOTO,K,WCHINO;J.Kyushiu Univ.,43,1970,p690
- 11) M.Tanaka;Dr.thesis,p.169
- 12) в. м.мебская, Горный Журнал, No.6,1966,p.59
- 13) L.C.McCABE,C.C.BOLEY;Chemistry of coal Utilization ,New York,1945, Chapter 7

DISCUSSION

R. WATSON (United States Bureau of Mines):

On examining the paper, it was not immediately obvious what the effect of particle size would have on the time for ignition of coal in a particular experiment; would it be a very drastic effect? In the experiments apparently coal of a given particle size distribution was used. Is this correct?

T. ISOBE (Hokkaido University, Japan): Yes, it is. After crushing, the coal sample was screened to make even the size of particles.

A.P. BUGDEN (Anglo American Corporation of South Africa Ltd.): Powdered coal of a rather fixed particle size was used?

T. ISOBE: The particle size was fixed at -48 mesh, because the larger the particle size, the more difficult it is to make ignition in the experimental apparatus.

R. WATSON: What would be the effect of increasing the particle size on the time of ignition of the coal in a given configuration.

T. ISOBE: There are two opposite effects of increasing the particle size, namely, one is the smaller the particle size is the larger is the cumulative surface area generated, therefore the ignition may be accelerated, the other is that small size coal powder piling hinders the air flow through itself, by this reason there exists less oxygen supply and it restrains temperature from rising. And the larger the quantity of coal the lower will be the ignition temperature. An attempt is to be made to start the spontaneous combustion from a lower temperature, e.g., lower than 30°C. But in this case both numerical calculations and experimental results have not yet been gained.

J. CUDMORE (Australian Coal Industry Research

Laboratories Ltd.): The effect of increasing particle size would tend to increase the time at which the onset of spontaneous combustion occurs. However particle size and effective surface area are only some of the factors which make a significant contribution to the promotion of the complex problem of spontaneous combustion.

R. WATSON: Does a small increase in particle size drastically change the possibility of ignition or is it just a nominal effect.

J. CUDMORE: In plotting the surface area of coal against particle size there is a dramatic increase in surface area with decrease in size. As mentioned previously particle size is an important factor in the promotion of spontaneous combustion.

R. WATSON: The U.S.B.M. recently did an experiment to determine whether or not oxygen self rescuers containing potassium superoxide would serve as a spontaneous combustion source if stimulated with water; they generate heat under these conditions. Some kinetic parameters for coal were derived based on small scale laboratory experiments with powdered coal. Then a much simplified theoretical calculation similar to this was done to determine the time for ignition based on the given heat source at the centre of the sphere. The theoretical calculations just assumed a homogenous block of coal but used the same basic kinetic parameters derived from powdered coal. The theoretical calculation for the ignition time corresponded almost exactly with the experimentally observed time and that kind of led to the thought that maybe the particle size effect for this type of reaction is not as strong as generally supposed.

A.J. HARGRAVES (B.H.P. Steel Division Collieries): Will more testing of spontaneous combustion be

undertaken in your apparatus with coal of different granulometry? Already -48 mesh is used - will both smaller coal and larger coal to be used in future experiments?

T. ISOBE: It is planned now. The Japanese coal mining industry was shrinking year by year and with it spontaneous combustion as a disaster risk in coal mines. Research was diminishing year by year influenced by this circumstance of the coal industry but in recent years, as a result of the oil crisis, the coal industry is vitalised again. Recently, many investigations on spontaneous combustion of coal have been resumed. Considering such a tendency, Dr. Higuchi, who has been in Australia more than one year, has commenced to experiment again on various kinds of coal at various size ranges. These further researches will commence this year or next year, probably in the laboratories of Hokkaido University.

K. BUNCH: (Dept. Mineral Resources): What forms of sulphur were present in the coal used? Would the forms of sulphur have had any effect on the time of ignition?

T. ISOBE: The form of sulphur present in the coal was pyrite and of course it is inorganic sulphur.

K. BUNCH: What effect does the sulphur have?

T. ISOBE: The influence of inorganic sulphur, of pyrite, is supposed to be one of the causes of spontaneous combustion, but in this research its influence is neglected. About 30 years ago a very noted researcher in Japan said that pyrite in Oyubari coal has a strong influence to accelerate spontaneous combustion phenomena. But this was denied by other researchers. For this reason the effect of pyrite in these phenomena is neglected.