Reaction Rates of Single Coal Particles: Influence of Swelling, Shape, and Other Factors

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1. INTRODUCTION

Coal particles burning in oxygen-vitiated and enriched atmospheres, at about 1000°C, have been shown by Previous work (1,2,3) to burn in the expected two-stage process of: volatiles combustion; followed by burn-out of the solid carbon residue remaining. The same work also showed that the solid residues burned according to the Nusselt-predicted (4) "square-law", by which the burn-out time (t_r) was directly proportional to the square of the initial particle diameter (d_o). However, although the agreement between prediction of the residue behavior and experiment was generally found to be adequate to good (1,2) there were several questionable points in the theoretical assumptions made in the modified (5,6) Nusselt theory used. These assumptions centered principally on the suggested behavior of the particles on swelling, and the ultimate effect this could have on the combustion behavior, particularly if the particles formed hollow cenospheres (7,8). Several questions were set up by this, as follows: (1) How much did the particles swell? (2) Was this swelling reasonably isotropic? (3) How did swelling change with coal rank? (4) Did the particles form cenospheres? (5) Did cenosphere formation, if any, affect the mechanism of burn-out, and if so how would this affect the theoretical analysis? (6) What influence did particles shape have on the final shape after swelling, and therefore on the combustion behavior?

To answer these questions as far as possible, a number of particles from each of the 10 coals used in the previous investigations (1,2,3) were photographed during combustion, and it was found that reasonably satisfactory answers to all six questions were obtained with, in addition, further information on swelling properties of coal particles.

The purpose of this paper is now to describe the photographic experiments carried out, the results obtained, and the answers that were provided, by these, to the questions given above.

2. EXPERIMENTAL

Whilst the coal particles were burning, in the combustion unit described in the previous papers (1,2,6), they were photographed using a continuously running camera adapted to take intermittent exposures.

2.1 Combustion Unit - The method of burning the particles was exactly the same as that described in the first two publications of this work (1,2). The particles, in the size range 0.5 to 2 m.m., were cemented to fine silica threads with a high temperature cement and then suspended, cantilever fashion, between two heating coils made of electrical resistance wire wound in flat spirals. These coils were about 1.5 m.m. across, and mounted with their planes horizontal about 1.5 m.m. apart. The coils were heated electrically, to about 1000°C.

2.2 Pyrolysis Unit - For a few experiments, carried out on one coal alone, the combustion unit described above was enclosed in a brass box, with observation windows, that could be flushed out with CO_2. This made it possible to observe the behavior, and measure the swelling of particles just pyrolysing without burning..

2.3 Optical Unit - To illuminate the particles, a 36-watt car headlamp bulb was placed at the focal point of a 10-cm. f.l. lens to produce a parallel beam of light. The particle combustion, or pyrolysis,unit, was placed in this parallel beam, about 20-cm. from the first lens, and about the same distance from a similar lens which then created a real image of the burning particle at about a one-to-one magnification. This image, therefore, could exist also as a real object, well clear of any heat source, that could be magnified to any required degree by a suitable short-focus objective close to this real object. The second image from this could then be projected onto a screen, or into a suitable camera.

2.4 Camera - The one used was a Cossor 35 m.m. Oscilloscope camera, with an adaptation to provide intermittent exposures on continuously moving film. A glass screen was lightly ground with abrasive and placed at the end of the camera tube, in the same relative position as that normally occupied by the Oscilloscope screen. The particle image provided by the optical unit was projected onto this screen, at a net magnification of about 5, and this image was then photographed (from the reverse side) by the Oscilloscope camera. This final stage diminished the image, but the overall magnification was still about 2. By trial and error it was found that the glass screen could not be too lightly, or too heavily ground: in the first instance the contrast between image and surroundings was too faint; and in the second, too little light was reaching the film.

2.5 Exposure Unit - Since the 35 m.m. recording strip was moving continuously, it would have blurred any time exposure that was of adequate duration to affect the emulsion used, even at the low speed of traverse involved. (The emulsion was on opaque recording paper, not on transparent film strip.) A rotating glass plate was therefore placed in the parallel light beam, between the particle and the second lens. As the plate rotated, it moved the image formed at the camera and, by adjusting the rate of rotation, the speed of motion of the image and recording paper could be matched (on the same principle as that used by the Fastax camera). This produced a clear image and, by incorporating a simple shutter, a series of single exposures could be taken. Finally, the rotation was synchronized with the camera by using gears and spindles of Meccano (a type of Errector set) to take a drive off the camera motor. Timing of the frames was then obtained by timing a given number of revolutions of the rotating plate.

2.6 Coal Preparation and Data - Information on grinding and sieving the coals is given in detail in the previous papers (1,2,6). They were crushed and ground by hand in a pestle and mortar, and then sieved mechanically using the complete sequence of British Standard sieves from 3/16" to 52 mesh (4760 to 295 microns). In these photographic studies, the particle sizes mostly used were about 2 m.m.

Table 1
Coal Analyses and Data

(1A) Ultimate Analysis (d.m.f.)

Coal	C	H	O	N	S	V	C_f	C_v	(C_v/C_f)
(1) Stanllyd (Blaunhirwaun)	93.00	3.35	1.59	1.33	0.73	9.9	90.1	2.9	0.03
(2) Five ft. (Deep Duffryn)	91.80	4.08	2.32	1.42	0.38	14.9	85.1	6.7	0.08
(3) Two ft. Nine -unknown-	91.20	4.35	2.54	1.65	0.26	28.8	71.2	20.0	0.28
(4) Red Vein (Cilely)	89.70	4.66	3.55	1.67	0.42	23.3	76.7	13.0	0.17
(5) Garw (Cwm Tillery)	88.90	4.99	4.50	1.33	0.28	30.6	69.4	19.5	0.28
(6) Silkstone (Elsecar)	86.90	5.79	5.50	1.51	0.30	41.5	58.5	18.4	0.49
(7) Winter (Grimethrope)	84.00	5.47	8.29	1.85	0.39	39.3	60.7	23.3	0.38
(8) Cowpen (Northumberland)	82.70	5.40	9.60	1.80	0.50	40.2	59.8	22.9	0.38
(9) High Hazel (Thorne)	81.90	5.57	10.52	1.58	0.43	40.7	59.3	22.6	0.38
(10) Lorraine (Faulquemont)	79.25	5.13	14.16	0.95	0.51	40.2	59.8	19.5	0.32

(1B) Proximate Analysis and Other Data

Coal	V.M.	H_2O	Ash	CO_2	B. S. Sw. No.	g/cc.	M	m
(1) Stanllyd	7.9	1.3	2.9	0.73	n.c.	1.38	0.871	3.06
(2) Five ft.	12.6	0.9	3.9	0.26	1	1.40	0.993	3.20
(3) Two ft. Nine	28.9	0.8	22.2	13.3	1	1.36	1.150	3.15
(4) Red Vein	20.5	1.0	1.6	0.04	6 1/2	1.34	1.794	3.01
(5) Garw	27.7	1.0	3.7	0.05	4	1.31	0.934	3.04
(6) Silkstone	39.6	1.3	1.7	0.35	4 1/2	1.28	0.690	3.00
(7) Winter	36.0	2.6	1.7	0.77	3	1.25	0.848	3.06
(8) Cowpen	34.6	7.3	4.1	0.95	1	1.27	1.000	3.17
(9) High Hazel	36.7	5.1	1.0	0.0	1	1.27	0.941	3.04
(10) Lorraine	35.0	5.0	5.9	0.52	n.c.	1.36	0.919	3.01

The coal analyses are given in Table 1, which also gives for the full particle size range, the size coefficients (M and m) in the empirical relation between weight (w_o) and initial diameter (d_o):

$$w_o = M.d_o^m \qquad (1)$$

where M and m are empirical constants determined experimentally. The method for determining M and m has already been described (2) but, briefly, required the weighing of groups of particles from a number of sieve cuts to determine w_o (the mean weight per particle) at a given mean sieve aperture as diameter, d_o. The best values of M and m were then determined by the method of least squares.

3. THEORY

The "square-law" relation referred to in the Introduction was first derived by Nusselt (4) for heat and mass transfer to and from a sphere. This theory, and necessary modifications for application to swelling coal particles, has been adequately covered in the previous papers and publications (1-3,5,6); the purpose of this section is to indicate how the theory may be modified further if needle-like coal particles are treated as cylinders instead of spheres.

For both systems the approximation of single diffusion of oxygen through stationary nitrogen is used. The Stephan flow (9) is also neglected since the previous studies (1,2) showed this to be a valid approximation for oxygen in air and vitiated air atmospheres (though not for enriched atmospheres (3)).

The starting point for both theories (sphere and cylinder) is Fick's Law for diffusion:

$$\dot{g} = -D(dN/dr) \qquad (2)$$

where $\dot{g}$ is the number of molecules diffusing across unit area in unit time; D is the diffusion coefficient; and dN/dr is the oxygen concentration gradient at any distance r from the center of the sphere.

The next step is to write the continuity equation which is slightly different for each system. For the sphere we have:

$$a^2.\dot{g}_s = r^2.\dot{g} \qquad (3a)$$

whilst for the cylinder

$$a.\dot{g}_s = r.\dot{g} \qquad (3b)$$

This makes the difference in the solutions for $\dot{g}_s$ since, on substitution for $\dot{g}$ and integrating, we have:

sphere: $$-\dot{g}_s = D(N_o - N_s) / a \qquad (4a)$$

cylinder: $$-\dot{g}_s = D(N_o - N_s) / a.\ln(r_o/a) \qquad (4b)$$

where the subscripts to N are for the main stream values and the solid surface values respectively; a is the particle radius; and r_o in eqn. (4b) is the distance at which the main stream value of N is reached. In eqn. (4a) this is taken as infinity, and the term in r_o vanishes. In eqn. (4b) the equation becomes meaningless, if r_o is taken as infinity. All we can do then is to consider the equation for the mass transfer coefficient k. This is:

$$\dot{g}_s = -k(N_o - N_s) \tag{5}$$

But the mass transfer coefficient is related to the Nusselt number for mass transfer by the definitive group;

$$Nu = k(2a)/D \tag{6}$$

For the sphere, it can be shown from eqn. (4a) that in quiescent conditions, Nu takes the value 2. Experimentally, it has also been shown by data (10) quoted by Gruber and Erk (11) that Nu also tends to a constant value, of 0.43, for the cylinder in quiescent ambient conditions. If we assume that thi holds generally, we than get the alternative equation for the cylinder:

$$-\dot{g}_s = 0.215D(N_o - N_s)/a \tag{4c}$$

which, clearly, differs from eqn. (4a) only by the factor 0.215. From either equation, we have that the specific reaction rate is inversely proportional to the radius. Integrating, as in the previous analyses for the sphere, we get for the variation of diameter with time:

$$d^2 = d_o^2 - t/K \tag{7}$$

where K is the burning constant, given by (2,5)

<u>for the sphere</u> $$K_s = \sigma / 3\rho_o D_o p_o (T/T_o)^{0.75} \tag{8a}$$

<u>and for the cylinder</u> $$K_L = K_s / 0.215 = 4.65K_s \tag{8b}$$

so a cylinder of radius a should still burn according to a square law, but take up to 4 or 5 times longer to burn out than a sphere.

3. <u>RESULTS</u>

3.1 <u>General Behavior</u> - In these photographic studies, between 30 and 40 particles were burned (compared with over a 1000 in the previous total-burnin time studies). The particles were mostly cubic in nominal appearance, this being the same principal basis of selection as in the previous studies, but a few were needle shaped particles selected to study the influence of shape.

The burning particles all exhibited the characteristic behavior of volatiles generation and combustion, with swelling during the volatiles combus phase; this was followed by residue burn-out. Diameters were measured from the photographic records and plotting the square of the diameter against frame number (as Time), to test eqn. (7), The Figures 1 and 2 show the type of plots obtained . Figure 1 is for the Stanllyd anthracite, and Figure 2 fo the Cowpen coal. In the latter, the effect of swelling is clearly illustrate by the sudden rise and fall of the curve at the start of combustion. Swelli in air is therefore a two-stage process; first there is a large expansion, followed by a contraction. In CO_2 there was only expansion, no contraction.

the end of the contraction, the line is seen to flatten out: this is the idue combustion. The curve of Fig. 2 is typical of all the bituminous ls, whatever their swelling number.

Swelling and Swelling Factor - f - The identification of the peak in Fig. 2 h the period of volatiles generation was more or less self-evident, but ther, positive identification was provided by simultaneously recording the ht output from the particle with a photocell. This technique had been d in the previous studies (1,2) to determine the total burning time, l it had been found during those that the period of volatiles evolution l combustion correlated with a characteristic trace in the record of the tocell output. This trace was a random high frequency oscillation due to flickering flame from the volatiles combustion. Identification of this ıracteristic trace, and comparison with the photographs, showed that the 'ticles started to swell a little in advance of the start of the volatiles ıbustion; the volatiles continued to burn right through the main expansion l contraction period; and the start of the residue combustion correlated .l with the start of the final linear portion of the plot of Fig. 2.

With this positive identification, measurements were then made of some 'egular shaped particles to check the degree of isotropism in the swelling.) particles selected for this were quite long, rectangular or needle-shaped 'ticles, the selection being based on the assumption that if they broke ı-isotropically, they would be the most likely to swell non-isotropically. the event, they swelled quite uniformly, all dimensions changing in approxi- :ely the same proportion, as with substantially all the other particles ıdied.

Swelling determinations were then carried out on selected particles of l the coals to determine their average swelling factors. The swelling :tor, f, was defined as the ratio (d_s/d_o), d_o being the initial, cold ımeter, and d_s being the diameter at the start of the residue combustion.) values of this ratio, f, are summarized in Table 2 for the ten coals. As ı be seen, the scatter is quite wide for any given coal, but the average very close to 1.5 for all the bituminous coals used, irrespective of the 3. swelling numbers. This result was quite unexpected, and it raises in əstion the meaning of such quantities as B.S. swelling number. The difference tween swelling factor and number is obviously dependent on the different perimental conditions in the methods of measurement. In contrast to the elling-factor measurements on single, unconstricted particles, as described ove, Swelling Number tests are made on groups of particles under some degree constriction, and are, therefore, partly able, and partly forced to swell to each other. Initially, at low volatile content in the bituminous range, ere is little loss, and therefore little increase in porosity. However, the volatile content (and loss) increases, there is more and more space adjoining particles for others to swell into, thus producing the character- tic inverted 'U' curve of the swelling or caking index against coal rank.

3 Residue Burn-Out - Study of the residue burn-out was the most crucial ınt examined. The particular point of interest here was in the change of ameter as the particle burned out. Sinnatt and others (7,8) had shown ny years ago that coal particles carbonizing in neutral or reducing atmospheres ll form hollow shells, generally known as cenospheres, the optimum tempera- rn of formation being between 600 and 700°C. If such a change occurred to e single particles before the residue combustion, then the theory of the sselt analysis, or any other similar analysis, would be quite inapplicalbe

since these depend on the assumption of reaction at the exposed nominal or superficial surface, alone; also the integral of the burning rate depends on the further assumption of uniform particle density, right down to zero radius.

This was in essence the basis of Ornings criticism (12) of one of the previous papers (2). Explicitly he mentioned the need to integrate to some finite radius as the lower limit, and not to zero radius. However, the experimental results do not support the expectations based on the cenosphere formation, but they do support the results based on the original assumption of uniform density right down to zero radius. The curves of the type of Fig. 2 show quite clearly that the results obey eqn. (10). This means that the rate of burning (dm/dt) is proportional to the radius or diameter, down to quite small radii. Few particles could be followed right down to zero radius because of the difficulty of measuring less than one millimetre on the recording strips, but most could be followed to between 70 and 90% loss of mass, so the agreement found over the measured range justified extrapolation to burn-out.

The slope of the burn-out section of the curves is given by eqn. (7) as 1/K. As a check on the magnitudes to be expected, these were calculated for many of the particles, and the values found ranged from 1000 to 2000 sq.cm./sec in good general agreement with the values previously reported (2). This is further substantiation of the conclusion that the particles are of uniform density right to the center. Because of the variation in the behavior of single particles, the scatter was about the same as that found for the total burning-time measurements made previously, but because of the much smaller numb of measurements made, these additional values have less meaning and precision compared with the previously determined values.

4. DISCUSSION

4.1 General - With the data available, there is little more that can usefully be added to comments already made on the foregoing results. To our mind these establish that the particles usually swell isotropically, with a swelling factor that is remarkably constant over a wide range of coal rank (10 to 40% V This alone is thought to be a point of considerable interest and importance. There was greater scatter in the swelling factor, f, between particles of the same coal than there was between the average values for different coals. This suggests that useful attention could well be directed towards pure maceral behavior as this might conceivably be responsible for the variations found. The particles evidently do not form cenospheres under these conditions though it is always possible that the peak swelling was a condition of true cenosphere formation, with destruction of the cenospheres as the temperature rose above the optimum for their formation. In this connection, it is not always realized that true cenosphere formation does not generally take place in oxidizing atmospheres above 1000°C. This again is thought to be a point worth further investigation. The only point not yet considered is the influence of shape factor.

4.2 Determination of Shape - To discuss the influence of shape, it is first necessary to determine what shapes the particles have. With the information on mass and diameter given in Table 2, considerable information can be obtained as to the most probable shapes of the particles. The mass/diameter data is correlated by eqn. (1). If we divide through by the coal densities, (Table 1), the data are converted to a volume/diameter correla Let us now consider a number of regular shapes as follows: (1) cube of side

(2) sphere of diameter d_o; (3) cylinder of diameter d_o and length d_o^{1+y}; (4) rectangular block of length d_o^{1+x}: (i) with square cross section of side d_o: (ii) with rectangular cross section of sides d_o and d_o^{1+y}; (5) spheroids, in both forms: (i) oblate and (ii) prolate, with minor axes of length d_o and major of length d^{1+x}. These all have volumes that can be related to the dimensions with a multiplying factor, F, as in the Table following:

Table 3

Particle Shape Factor, F

3. (A) Regular Shapes

	Volume	Factor (F)
1. Cube	d^3	1
2. Sphere	$(\pi/6)\,d^3$	0.524
3. Cylinder	$(\pi/4)\,d^{3+x}$	0.7855
4. Rectangular block		
(i) regular	d^{3+x}	1
(ii) irregular	d^{3+x+y}	1
5. Spheroid		
(i) oblate	$(\pi/6)\,d^{3+2x}$	0.524
(ii) prolate	$(\pi/6)\,d^{3+x}$	0.524

3. (B)	Coal Data (x + y)	F	K(calc)	K(expt)	K(calc)/K(expt)
1. Stanllyd	0.06	0.63	2680	2125	1.26
2. Five ft.	0.20	0.708	1725	1290	1.34
3. Two ft. Nine	0.15	0.845	1365	1470	0.93
4. Red Vein	0.01	0.592	1500	1475	1.02
5. Garw	0.04	0.713	1335	1610	0.95
6. Silkstone	0.00	0.54	1080	1110	0.97
7. Winter	0.06	0.674	1095	1125	0.97
8. Cowpen	0.17	0.787	1055	1060	1.00
9. High Hazel	0.04	0.735	1075	1450	0.74
10. Lorraine	0.01	0.675	1165	992	1.07

From this it can be seen that the cube and rectangular blocks have F factors of unity; the sphere and spheroids, values of 0.524; and the cylinder is intermediate, at 0.7855. For the data quoted, the particles chosen were those that, by eye, looked closest to cubes, so we expected to find F factors close to unity. In fact, as Table 3 shows, the values indicated that the shapes approximated more closely to something between the spheroid and the cylinder than to a cube or rectangular block. Table 3 also gives the experimental and calculated values of K obtained previously (2); there seems to be no correlation between the (x+y) exponent difference, or the F factors. We therefore conclude that treating the particles as spheres was an adequate approximation to reality, the more so as the particles definitely derived a more rounded shape as they swelled, in spite of the general retention of their original shape. The final difference between the calculated and experimental values of K is most probably due to random scatter. Any closer practical identification with shape will require more precise experiments than those reported here.

4.3 Influence of Shape - Although determination of shape did not provide any further practical interpretation of the available data, the factor of shape can, nevertheless, be usefully considered and discussed in general. Shape may be partly a function of the inherent physical properties of a given coal that control the shape on breakage, but Perry (13) has shown that it is also dependent on the type of grinder used. Perry reported that a disc mill produced lamellar shapes whilst those from a hammer mill were polyhedral, tending to cubical. With decreasing particle size, the lamellar shapes tended to vanish, and even the disc mill produced substantially polyhedral shapes at very small sizes. In our experiments, the particles were crushed by hand, in a pestle and mortar and, as described above, their shapes seemed to approximate most closely to spheroids and cylinders.

In influencing combustion behavior, we might expect that, broadly speaking, the smaller the radius of curvature of any part of the particle surface, the faster that area would be likely to react, since the boundary layer above that part should be a little thinner. It is difficult to say for certain, however, from a study of the photographs, that this does or does not occur; irregularities in the shapes of the particles are maintained for quite an appreciable length of time - as long as 10 or 20 seconds - but most of the particles appeared to have been reduced to good approximations to spheres by the time they were half burned. The photographs in some instances were misleading as the ash would occasionally remain as a fairly coherent, though fragile, tracery, in the center of which the glowing, shrinking sphere could be clearly seen by eye, though the photographs showed only the barely changing outline of the ash. This was generally the case with the high-ash Two Ft. Nine coal, but occasionally happened with the others.

What we would suggest, from both the visual and photographic studies of the particles, is that reaction is in fact fastest at exposed projections, and sharply curving surfaces. This means that shapes like cubes, prolate spheroids, and polyhedral shapes in general will be reduced approximately to spheres by the time they are half burned. Short cylinders and short rectangular blocks of near uniform cross-section would therefore burn down first to something approaching prolate spheroids, and thence again would reduce to spheres. This means that excess material might burn off fairly rapidly, and the overall behavior would then approximate to spheres of diamet equal to the cube side, the shorter side of the rectangular block, or the minor diameter of the prolate spheroids. Since these are the dimensions most likely to determine whether or not a given particle would remain on, or pass through, a given sieve mesh, it may well substantiate and justify the successful use of the sieve mesh dimension in specifying the particle diamete to be used in the combustion calculations.

Other shapes such as needles, long cylinders, long regular blocks, or prolate spheroids with a big ratio of major to minor axis would be expected to burn at rates rather closer to those expected of regular cylinders. The square law relation of eqn. (7) should still obtain, but the burning rates and overall burning times should be rather longer. This expectation was neve tested quantitatively but it could quite possibly account for some of the scatter in burning times found at any particular given diameter.

Finally, there are shapes like oblate spheroids, flat rectangular plates and lamellae. The behavior of these has yet to be investigated either theoretically or experimentally, but our expectation is that they would very likely burn in from the edges rather fast, giving burning times many times in excess of expectation on the basis of either the total mass involved, or on sieve diameter. It is also likely to be sharply dependent on the orientation of the plane or flatter surface to the horizontal or vertical as this could strongly influence the natural convection currents and therefore the boundary layer thickness. This, however, is an area of investigation still open to study.

5. CONCLUSIONS

The conclusions that may be drawn from this study are in answer to the questions set out in the Introduction.

(1) Particles swell or not according to coal rank. Particles from anthracites (under 5% V.M.) swell negligibly or not at all. Particles from bituminous coals, on the other hand, (greater than 10% V.M.) swell in air by a net factor of about 1.5, this factor being substantially independent of coal rank.

(2) The swelling process is in two stages: first an expansion to 2 or 3 times the original diameter, followed by a contraction down to the final diameter of 1.5 times the original diameter. In CO_2, the swelling finishes at the end of the first stage; there is no contraction which presumably, therefore, is conditioned by the presence of oxygen.

(3) In swelling, the process was reasonably isotropic, and apparently uniform throughout, with no cenosphere formation.

(4) In burn-out, the particles evidently burned uniformly at the exposed surface only. There was no evidence of internal burning (as is only to be expected with boundary-layer diffusion control of the reaction). The diameters therefore dimished with time quite regularly according to the equation:

$$d^2 = d_o^2 - t/K$$

with values of the burning constant K in agreement with those obtained previously from studies of the "integrated" or total burning times.

(5) Finally, shape appeared to have no detectable effect on the burning rates, other than maybe to increase the scatter in the burning times. Detection of any such effect will almost certainly require more accurate studies, using more precisely specified materials, both with regard to composition as well as shape.

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Table 2

Values of Swelling Factor, f (d_s/d_o)

		c%	V.M. %	Values of f	Mean (f)
1.	Stanllyd	93.0	9.9	1,1,1	1
2.	Five ft.	91.8	14.9	1.5, 1.25, 1.9	1.55
3.	Two ft. Nine	91.2	28.8	1.1, 1.25, 2.2	1.48
4.	Red Vein	89.7	23.3	1.75, 1.6, 1.7 1.7, 1.9, 1.7	1.72
5.	Garw	88.9	30.6	1.8, 1.6, 1.4 1.9, 1.5	1.64
6.	Silkstone	86.9	41.5	1.8, 1.4	1.6
7.	Winter	84.0	39.3	1.3, 1.1, 1.6 1.9, 2.0	1.58
8.	Cowpen	82.7	40.2	1.6, 1.5, 1.9	1.67
9.	High Hazel	81.9	40.7	1.4, 1.5, 1.4 1.8, 1.6, 1.7	1.56
10.	Lorraine	79.3	40.2	1.3, 1.5, 1.5 1.8, 1.6	1.54

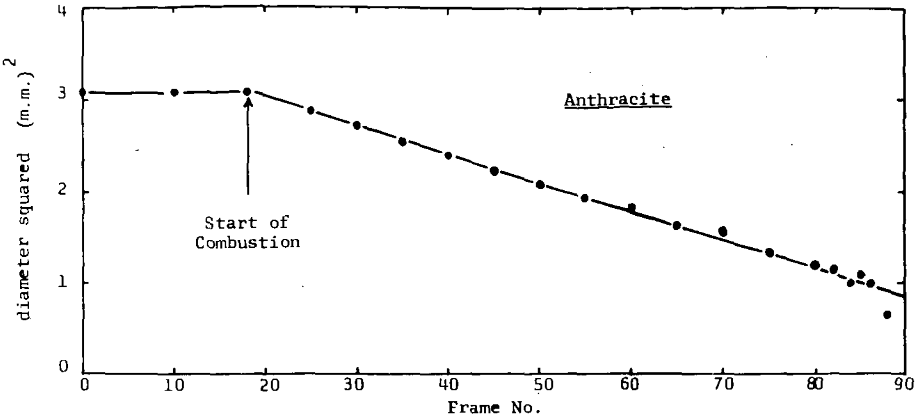

Figure 1 - Variation of diameter squared with time of burning anthracite particle (Stanllyd)

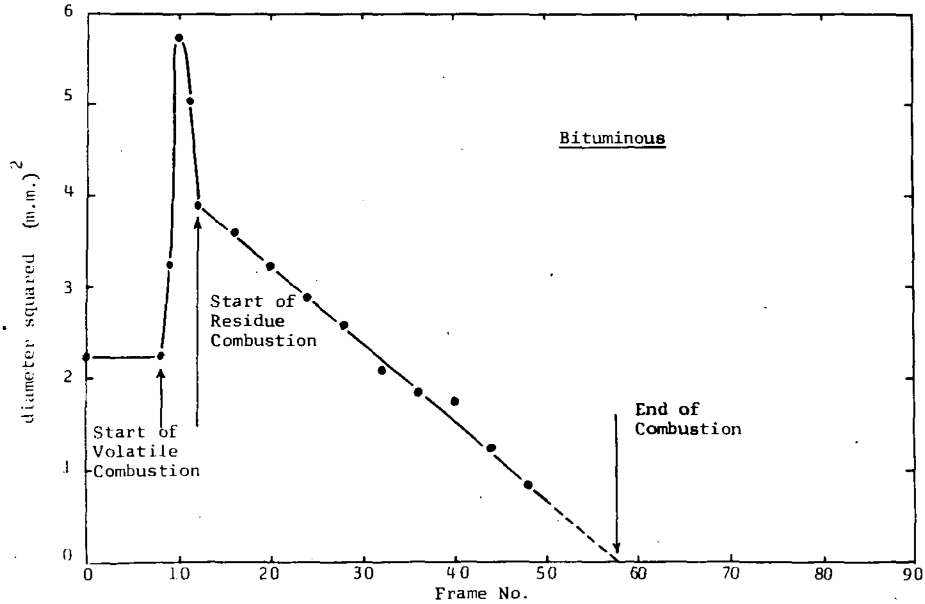

Figure 2 - Variation of diameter-squared with time of burning bituminous coal particle (Cowpen)