FLAME VITRIFICATION AND SINTERING CHARACTERISTICS OF SILICATE ASH

ERICH RAASK

Technical Planning and Research Division of Central Electricity Generating Board, Kelvin Avenue, Leatherhead, Surrey, UK

The silicate species constitute the bulk of the mineral matter in most coals, and the formation of boiler deposits depends largely on the physical and pyrochemical changes of the ash residue constituents. In this work the mode of occurence of coal silicate minerals, and the flame induced vitrification and sodium initiated sintering mechanisms have been studied. The pulversized coal flame temperature is sufficiently high to vitrify the quartz particles. On cooling some devitrification occurs and the rate of sintering depends largely on the ratio of glassy phase to crystalline species in the ash. The flame volatile sodium captured by the vitrified silicate particles can initiate the coalescence of deposited ash by viscous flow and the rate of sintering is markedly increased by the alkali-metal dissolved in the glassy phase.

The flame imprinted characteristics of pulverized coal ash relevant to boiler slagging, corrosion and erosion have been discussed previously (1,2). The silicate minerals constitute between 60 and 90 per cent of ash in most coals and boiler deposits are largely made up from the silicious impurity constituents. This work sets out first to examine the mode of occurrence of the silicate mineral species in coal followed by a characterization assessment of the flame vitrified and sodium enriched silicate ash particles. The ash sintering studies are limited to investigations of the role of sodium in initiating and sustaining the bond forming reactions leading to the formation of boiler deposits.

SILICA (QUARTZ) AND SILICATE MINERAL SPECIES IN COAL

The quartz and alumino-silicate species found in most coals constitute the bulk of combustion ash residue. The alumino-silicates include muscovite and illite which contain potassium, and kaolinite species (3,4,5,6). The silica (SiO_2) and alumina (Al_2O_3) as determined by chemical analysis are present in alumino-silicates on an average weight ratio of 1.5 to 1 as reported by Dixon et al. (6). The excess of silica represents the amount of quartz in coal mineral matter:

$$(SiO_2)_q = (SiO_2)_t - 1.5(Al_2O_3) \qquad 1)$$

Where $(SiO_2)_q$, $(SiO_2)_t$ and (Al_2O_3) denote respectively the quartz, total silica and alumina contents of ash.

An approximate amount of potassium alumino-silicates in coal mineral matter can be obtained from the potassium oxide (K_2O) content of ash. The amount of non-silicate potassium species is small in most coals and the silicate minerals contain on average 11 per cent K_2O by weight (6). Thus the potassium alumino-silicate content of coal mineral matter (K_{AL-SIL}) by weight per cent is:

$$K_{AL-SIL} = \frac{K_2O}{0.11} = 9.1\ K_2O \qquad 2)$$

where K_2O denotes the potassium oxide content of ash.

The total amount of silicate minerals equals approximately the sum of SiO_2, Al_2O_3 and K_2O in ash, and an estimate of kaolinite species is thus given by:

$$\text{Kaolinite} = (SiO_2 + Al_2O_3 + K_2O) - (\text{Quartz} + \text{Potassium Silicates}) \quad 3)$$

Table 1 gives the SiO_2, Al_2O_3 and K_2O contents of some US and British bituminous coal ashes (4,7) which were used to calculate the approximate amounts of quartz, potassium alumino-silicate and kaolinite species in the mineral matter.

Table 1: Silicate Species in Mineral Matter of British and US Bituminous Coals

Type of Coal		Ash Constituents, Weight Per Cent of Ash			Mineral Species, Weight Per Cent of the the Total		
		SiO_2	Al_2O_3	K_2O	Quartz	Pot. Alum. Silicates	Kaolinite
Low Silica	British	31.1	18.1	1.2	3.9	10.9	26.2
	US	29.2	14.2	1.5	7.9	13.6	23.6
Medium Silica	British	46.5	22.8	2.8	12.3	25.5	34.3
	US	46.6	27.8	1.1	4.9	10.0	60.6
High Silica	British	55.5	30.0	2.7	10.5	24.5	53.2
	US	56.5	32.2	2.6	8.0	23.6	59.7

Table 1 shows that the kaolinite species constitutes up to 60 per cent of the coal mineral matter. The amount of potassium alumino-silicates, chiefly muscovite and illite is between 10 and 25 per cent, and the quartz content is usually below 12 per cent. The alumino-silicate minerals contain frequently iron, calcium, magnesium and sodium as part replacement for potassium and partly incorporated in the kaolinite structure. Also, the silicate minerals occur as hydrated species with the inherent water content of between 2 to 5 per cent, thus the silicious mineral contents are likely to be about 5 per cent higher than those given in Table 1.

The silica and alumina contents of the first two samples are exceptionally low for bituminous coal ashes. The usual concentration range of silica is 35 to 55 per cent and that of alumina is 20 to 30 per cent thus the alumino-silicate species together with quartz constitute between 6o to 90 per cent of the bituminus coal mineral matter.

The silicate species occur in coal chiefly as separate strata and large particle inclusions, and this mode of occurrence is termed the "adventitious" mineral matter. Fig. la shows a typical sample of the adventitious silicate mineral particles, density separated from pulverized coal. The density separation technique does not remove the small silicate particles, chiefly alumino-silicate species dispersed in the coal substance (Fig. lb). The average ash content of bituminous coals utilized in electricity generating power stations is usually between 12 and 20 per cent (4,8) and about one quarter, 3 to 5 per cent fraction is present as the inherent ash.

The mineral elements can be held in the coal substance as organo-metal salts, and also as a result of molecular adsorption and co-valent bonding. The mineral species dissolved in coal pore water, chiefly chlorides can also be considered as a part of the inherent mineral matter. The lignites and sub-bituminous coals can have a high fraction of the mineral elements, chiefly sodium, calcium and also aluminium and iron chemically combined in the fuel substance (9,10). The chemical reactivity and porosity of the fuel matrix decreases with the increase of coal age from lignite to bituminous rank. The loss of carboxyl, hydroxyl and quinone bonding sites in the fuel matrix results in a low "chemical" mineral matter content of bituminous coals.

CHLORIDE IN COAL PORE AND SEAM WATER

Chloride minerals are rarely found in coal in the form of solid species because of high solubility of sodium, calcium and trace metal chlorides in coal strata waters. The "inherent" water content of coal is related to its porosity and thus the moisture content of lignite deposits can exceed 40 per cent decreasing to below 5 per cent in fully matured bituminous coals (11). Chlorides, chiefly associated with sodium and calcium constitute the bulk of water-soluble matter in British bituminous coals (12) and Skipsay (13) has found that the distribution of chlorine coals was closely related to the salinity of mine waters. Hypersaline brines with concentrations of dissolved solids up to 200 kg m^{-3} occur in several of the British coalfields.

The mode of formation of hypersaline brines has been discussed by Dunham (14) concluding that the connate waters were of marine origin formed by the osmotic filtration through clay and shale deposits. The salinity of the brine ground waters increases with depth and when they are in contact with fuel bearing strata, correspondingly more chloride is taken up by the fuel. However, according to Skipsey (13) the high rank bituminous coals because of their low porosity are unable to take up large amounts of the chloride and associated cations, and the chlorine content rarely exceeds 0.2 per cent. The chlorine content of low rank bituminous coals can reach one per cent and correspondingly the sodium fraction associated with chlorine will amount up to 0.4 per cent of coal. That is, the ash from a high chlorine coal can contain up to 3 per cent of flame volatile sodium. The chlorine content of lignites and sub-bituminous coals is usually low, below 0.1 per cent, and sodium is held chiefly in the fuel substance in the form of organo-metal components (9,10).

All coals contain some sodium combined in the alumino-silicate species which will remain largely involatile in the flame. The ratio of the silicate sodium to non-silicate sodium varies over a wide range. The alkali-metal is present chiefly in the silicates in low chlorine bituminous coals, but in the high chlorine bituminous coals and in many lignites and sub-bituminous coals it is present mainly in a flame volatile form.

FLAME VITRIFICATION OF SILICA MINERALS

A characteristic feature of flame heated ash is that the particles are spherical in shape as shown in Fig. 2. The transformation of the angular silicate mineral particles in pulverized coal to spherical particle ash is a result of the surface tension force acting on the vitrified species. The stress (f) on a non-spherical surface section of the particle is:

$$f = 2\gamma/\rho \qquad 4)$$

where γ is the surface tension of glassy silicate and ρ is the radius of curvature. It is evident from equation (4) that the stress is inversely proportional to the radius of curvature and thus the small sharp-edged particles are first to take a spherical form.

Frenkel (15) has shown that time (t) required to transform an angular particle to sphere is given to first approximation by:

$$r = r_0 e^{-t/z} \qquad 5)$$

where

$$z = 4\pi\eta r_0/\gamma \qquad 6)$$

and r is the distance of a point on the original surface from the center of a sphere of equivalent volume having radius r_0, η is the viscosity and γ is the surface tension.

Equation 5 can be used to calculate the approximate time required for a particle to assume a spherical shape when the surface tension, viscosity, size and initial shape of particle are known. Alternatively, an estimate of the viscosity for the change to take place, can be made when the residence time of particles at a given temperature is known. Table 1 gives the calculated values of viscosity when the time for the change is one second. It was assumed that the thickness of moving surface layer was about ten per cent of the radius, and the surface tension of fused ash was taken to be 0.32 N m^{-1} as measured previously (16).

Table 2: Calculated Viscosities for Spheridization of Different Size Silicate Particles

Particle Radius, μm	0.01	0.1	1	10	100
Viscosity, N s m^{-2}	2.5×10^7	2.5×10^6	2.5×10^5	2.5×10^4	2.3×10^3

Table 2 shows that the small irregularly shaped particles transform to spheres in a coal flame when the viscosity of the material is several orders higher than that required for bulk flow under gravity, which is about 25 N s m^{-2}. A laboratory technique was used to determine the minimum temperature at which coal mineral species are transformed to spherical shapes (17). Particles of 10 to 200 μm in diameter were introduced into a gas stream and then passed through a vertical furnace. The temperature of the furnace was varied from 1175 to 2025 K and was measured by a radiation pyrometer and by thermocouples placed in the furnace. The residence time of particles in the furnace was between 0.2 and 0.5 sec. depending on the particle size.

Fig. 3a shows a surface-fused silicate particle heated to a temperature some 25 K lower than that required for its spheridization. Fig. 3b shows a spheridized particle heated in the laboratory furnace. Fig. 4 shows the temperature range at which the shape change of different coal mineral particles occurred. The chlorite mineral contain some quartz and the two species spheridized at markedly different temperatures as shown by curves D_1 and D_2.

The temperature of mineral particles in the pulverized coal flame exceeds 1800 K (Fig. 5), and it is therefore to be expected that all particles with the exception of large size quartz will vitrify and change to spherical shapes. Fig. 6a shows a surface-fused but non-spherical quartz particle found in a sample of fly ash captured in the electrical precipitator. Occasionally ellipsoidal particles of alumino-silicates (Fig. 6b) can be found in the ash indicating that the high temperature residence time was slightly too short for complete spheridization. However, the majority of the ash particles appear to be spherical as shown in Fig. 2.

The spherical silicate ash particles, when viewed at close-up range appear to host a large number of sub-micron particles at the surface (Fig. 6c). The microids could be silicate crystalloids precipitated from the vitrified phase or sulphate fume particles formed from the non-silicate coal minerals (18). The latter are soluble in a dilute acid (HCl) solution and Fig. 6d shows the acid etched particles. Clearly, most of the microid particles were dissolved and the leach solution contained sodium and potassium sulphates.

Another diagnostic test for silicate ash is to treat the particles with hydrofluoric (HF) acid solution (18,19,20). The acid will dissolve the glassy phase revealing skeletons of crystalline species which may be in the form of mullite needles (Fig. 6e) or quartz crystalloids (Fig. 6f). The ratio of the glassy phase to crystalline species varies from particle to particle depending on the original composition of the silicate minerals, the capture of volatile sodium and the rate of cooling of the flue gas borne ash.

The flame imprinted characteristics of silicate mineral species from the point of view of subsequent sintering are summarized in Table 3.

Table 3: Flame Vitrification and Recrystallization of Silicates

Constituent Species	Particle Vitrification		Recrystallization Tendency	Glass Content
	Temperature Range, K	Extent		
Quartz	1700 to 1900	Medium	Low	Medium
Kaolinite	1600 to 1700	High	High	Medium
Potassium Alumino-silicates	1400 to 1600	High	Low	High

The relative amount of coal mineral quartz surviving in the pulverized fuel flame depends on the particle size and temperature. In the intense combustion of cyclone fired boilers the flame temperature exceeds 2000 K and the quartz particles of all sizes will vitrify. Some quartz particles in the crystalline form will survive the flame treatment in pulverized coal fired boilers and the ash may contain 25 per cent of the original coal quartz in the crysalline form (21).

The kaolinite mineral species in coal contain some sodium, calcium and iron in the crystalline structure (6) and the presence of fluxing metals enhances vitrification of the flame heated particles. The high temperature crystalline form of kaolinite species is mullite and the characteristic needle shapes of mullite (Fig. 6e) are frequently found in large, above 5 μm diameter particles. The mullite needle crystals in ash are always embedded in a glassy phase of the large particles and it appears that the small, below 5 μm diameter particles of the flame heated kaolinite species are not extensively recrystallized on cooling. The crystalline species of illite and muscovite are not found in the flame heated ash and thus it is likely that the potassium alumino-silicates remain on cooling largely in the form of glassy particles.

The inherent silicate ash (Fig. 1b) will coalesce on combustion first to a sintered matrix inside the burning coal particle and also to small slag globules at the surface of coke residue. Fig. 7a shows the slag globules on a coke particle separated from pulverized coal ash and Fig. 7b shows a lace skeleton of sintered ash in another coke particle revealed after combustion at 900 K.

During combustion of the mineral rich coal particles in the pulverized fuel flame ash envelopes may be created which can take the form of cenospheres as shown in Fig. 7c and d. The gas bubble evolution leading to cenosphere formation has been discussed previously (16,22) and the fly ash usually contains between 0.1 and 2 per cent by weight of the lightweight ash. The mineral rich coal particles may leave the combustion ash residue also in the form of plerosphere (spheres-inside-sphere) as shown in Fig. 7e.

The above examples show that the inherent silica ash particles undergo extensive coalescence by sintering and slagging during combustion of the host coal particles. However, the adventitious ash retain the particle identity in the flame and the processes of sintering and slagging take place after deposition on boiler tubes.

TRANSFER OF FLAME VOLATILE SODIUM TO SILICATES.

The coal sodium originally present as chloride or organo-metal compounds is rapidly volatilized in the pulverized coal flame (23). Subsequently the volatile species are partly dissolved in the surface layer of flame heated silicate particles and partly sulphated in the flue gas (8). The formation of sodium sulphate can proceed via two routes:

Route 1 - In the Flue Gas

$$\underset{2NaX}{2X} + \underbrace{\left[2Na + H_2O + SO_2 + \frac{1}{2}O_2\right] \rightarrow 2HCl + Na_2SO_4}_{\text{Vapour phase reactions}} \rightarrow \underset{\text{Particles}}{\overset{\text{Fume}}{Na_2SO_4}}$$

Route 2 - At the Surface of Ash Particles

$$\underset{2NaX}{2X} + \underbrace{\left[2Na + H_2O\right] \rightarrow 2HCL + Na_2O}_{\text{Vapour phase reactions}} \rightarrow \underbrace{Na_2O + SO_2 + \frac{1}{2} \rightarrow Na_2SO_4}_{\text{Reactions at ash surface}}$$

Route 1 for genesis of sodium sulphate fume can be described as the non-captive formation and route 2 as the captive formation.

Some potassium sulphate can also be formed via the two routes. Potassium is present in coal chiefly in the form of potassium alumino-silicates (Table 1) and a large part of the alkali-metal will remain involatile in the flame heated silicate particles. Some 5 to 20 per cent of the potassium is released for sulphation (24) which takes place partly at the surface of the parent particles (25) and partly via the volatilization routes as described above. However, sodium sulphate content of fly ash and chimney content of fly ash and chimney solids is always higher than that of potassium sulphate.

The distribution of the flame volatile sodium between the ash silicate and sulphate phases is markedly influenced by the temperature and residence time of the ash particles in the flame. The high temperature of large boiler flame reduces the viscosity of vitrified silicate particles and as a result a large fraction of the volatile sodium is dissolved in the silicate phase. On average 60 per cent of the sodium is dissolved in the silicate ash particles (6) the remainder being present as suphate fume particles in the flue gas (20).

THE MECHANISM AND MEASUREMENTS OF SODIUM ENHANCED SINTERING

The formation of sintered ash deposits on boiler tubes requires first a close, molecular distance contact between the particles followed by a growth of particle-to-particle bridges chiefly by viscous flow. Sodium sulphate phase together with some potassium sulphate may play a significant role in the initial stage of sintering by bringing the silicate particles together as a result of surface tension. Sodium sulphate melts at 1157 K but mixed alkali-metal sulphates can form a molten phase at lower temperatures (26).

Once the close contact between the silicate particles has been established a viscous flow of the particle surface layer can commence and the sinter bonds are established according to Equation 7 as discussed by Frenkel (15):

$$\frac{x^2}{r^2} = \frac{3\gamma t}{2\eta r} \qquad 7)$$

where x is the radius of neck growth between the spherical particles of radius r, γ is the surface tension, η is the viscosity of fused ash, and t is the time. The $(x/r)^2$ ratio can be taken as a criterion of the degree of sintering, i.e. the strength of boiler deposit (s) developed in time t, that is:

$$s = k\left(\frac{x}{r}\right)^2 \qquad 8)$$

and the rate of deposit strength development is:

$$\frac{ds}{dt} = \frac{3k\gamma}{2\eta r} \qquad 9)$$

where k is a constant.

Equation 9 shows that the rate of ash sintering, i.e. the development of cohesive strength of a deposit matrix is proportional to the surface tension and inversely proportional to the viscosity. The surface tension and particle size are not markedly changed by dissolution of sodium, iron or calcium oxides in the glassy phase of silicate ash. However, the viscosity is markedly changed by the oxides. In particular, an enrichment of sodium in the surface layer of the silicate ash particles can lead to a high rate of sintering.

Some of the flame volatile sodium is dissolved in the vitrified silicate ash particles before deposition and an additional amount of sodium is transferred from the sulphate to silicate phases during sintering. The reaction between sodium sulphate and silicates at ash sintering temperatures has been monitored by thermo-gravimetric measurements. Some of the results are given in Table 4.

Table 4: Weight Loss of Sulphates and Sulphate/Silicate Mixtures

Sample	Na_2SO_4	Na_2SO_4/Kaolin	Na_2SO_4/Ash	$CaSO_4$	$CaSO_4$/Kaolin	$CaSO_4$/Ash
Loss Initiation Temperature, K	1425	1085	1175	>1525	1275	1275

Anhydrous sulphate samples and the suphate/silicate mixtures (50 per cent by weight sulphate) were heated in air at the rate of 6 K per minute.

The results in Table 4 show that the reaction between sodium sulphate and kaolin commenced at 1085 K with the release of SO_2 and SO_3

$$Al_2O_3 + xNa_2SO_4 \rightarrow xNa_2O.Al_2O_3.2SiO_2 + x(SO_2, SO_3) \qquad 10)$$

A typical bituminous coal ash required a higher temperature of 1175 K for the sulphate decomposition reaction.

The transfer of sodium from the sulphate of silicate phase will reduce the viscosity of the glassy material resulting in an enhanced rate of sintering. At higher temperatures, above 1275 K, calcium sulphate starts to dissociate in the preence of kaolin and thus calcium oxide will be available for the sintering reactions. The specific roles of coal calcium and also the iron mineral species in ash sintering and slag formation have been discussed previously (2).

The sintering rates of bituminous, sub-bituminous and lignite coal ashes of different sodium contents can be determined by the electrical conductance measurements. In this method the conductance across an ash compact is measured and it is an indication of the degree of sintering (27). The sodium ions in the low viscosity glass and molten sulphate are the conductive species and the conductance continuity is provided by the sinter bridges between the particles.

Fig. 8 (curve B) shows that sub-bituminous coal ash of high (6.3 per cent) sodium oxide content commenced sintering at 1100 K as determined by the conductance measurements. The results (27) suggest that the amount of sodium in some ashes are sufficiently high both to initiate and sustain a rapid rate of sintering below 1200 K. In contrast, with low sodium coals the rate of ash sintering and the formation of boiler deposits are related to the calcium and iron contents of coal mineral matter. Several empirical formulae have been proposed for predicting the deposit forming propensity of the lignitic and bituminous coal type ashes based on the sodiu content (28). These formulae indicate that a rapid build-up of boiler deposit is to be expected when sodium (Na_2O) content of bituminous coal exceeds 2.5 per cent, and that of lignite and sub-bituminous coal ashes is above 4 per cent.

The lignite type ashes have comparatively low fouling propensity when the sodium content is below 4 per cent because of the limited amount of clay minerals available for sintering reaction. That is, in some lignite and sub-bituminous coals there is an excess of sodium and calcium available for the high temperature reactions, and the rate of deposit formation depends on the silicate content of ash (2,9,30). The bituminous coal type ash has an excess of silicates, i.e. the ash is pyrochemically acidic snd the rate of sintering depends on the availability of sodium, calcium and iron species in the flame heated deposit material.

The formation of sintered ash deposits is governed chiefly by viscous flow, and the rate of sintering (S_r) can be expressed in terms of the ratio of glassy material to crystalline species of silicate ash ($R_{g/c}$) and the viscosity of the glassy phase (η):

$$S_r = \kappa_1 (R_{g/c}) \frac{1}{\eta} \qquad 11)$$

where κ is a constant. The characteristics of flame heated silicate particles, (Fig. 4 and Table 3 in Sect. 4) suggest that the vitrified potassium alumino-silicate particles and the below 5 μm diameter kaolinite particles are first to sinter after deposits. The particles will have a high glass content and the small size enhances sintering as evident from equation (10). It is therefore to be expected that the presence of floor material (6) should enhance sintering and

large particle quartz particles would retard the deposit formation. This applies in the absence of large concentrations of the flame volatile sodium, and non-silicate calcium and iron compounds. The flux material oxides will both increase the ash glass content and reduce the viscosity for sintering, Equation 11, and the composition of original silicate species is less important.

CONCLUSIONS

Silicate Minerals in Coal

The silicate minerals, kaolinite and potassium alumino-silicate species together with quartz constitute the bulk of mineral matter in most coals. The approximate amounts of different silicate species of the bituminous coal mineral matter can be estimated from ash analysis.

Flame Volatile and Silicate Sodium in Coal

Sodium is rapidly volatilized in the flame when it occurs in a non-silicate compound form, chiefly associated with chlorine in bituminous coals and combined with organic compounds in the lignite and sub-bituminous fuels. The fraction of sodium combined with coal silicates remains largely involatile in the pulverized fuel flame.

Flame Vitrification and Spheridization of Silicate Particles

The alumino-silicate particles vitrify and take a spherical shape in the flame and are partially recrystallized on cooling. Micro-needles of mullite up to 10 μm long and crystalloids of quartz are the principal devitrification products enveloped in a glassy material matrix. Large quartz particles originally present in coal are only surface vitrified and do not spheridize in the flame. The coalescence by sintering and fusion of the small alumino-silicate particles dispersed in the fuel substance occurs when the host coal particles burn in the flame. The products are sintered ash skeletons, censopheres and plerospheres up to 250 μm in diameter.

Sodium Transfer to Silicate and Sulphate Phases

The flame volatile sodium is partly dissolved in the surface layer of vitrified silicate ash particles and partly sulphated. The sulphate particles, 0.1 to 2 μm in diameter can form on the surface of ash particles or in th flue gas via vapour phase reactions followed by sublimation on cooling. Some potassium sulphate is also formed from a fraction of the alkali-metal released on vitrification of potassium alumino-silicates in the flame.

Initial Stage in Ash Sintering

The sulphate phase can initiate ash sintering by bringing the silicate particles to close contact as a result of the surface tension force. Subsequent sintering proceeds by viscous flow and the rate of sinter bond growth is proportional to the surface tension of silicate glassy phase and inversely proportional to the particle size and the viscosity. The latter changes exponentially with temperature and thus the viscosity of silicate ash particles governs the rate of sintering at different temperatures.

Decomposition of Sulphate on Silicate Ash Sintering

Sodium sulphates in the initial material deposited on boiler tubes will be decomposed by the pyrochemically acidic silicates in ash when the deposit temperature exceeds 1085 K. The transfer of sodium from the sulphate to silicate

phase reduces the viscosity of the glassy material of silicate ash thus increasing the rate of sintering.

Sintering of High Sodium Coal Ashes

Some lignite and sub-bituminous coal ash contain sufficiently high quantities of the flame volatile sodium to initiate and subsequently to sustain a high rate of ash sintering leading to a rapid build-up of boiler deposit. With most bituminous coal ashes the volatile sodium plays a role in initiating sintering but the subsequent deposit and slag formation depends largely on the presence of calcium and iron flux oxides. In general terms, the rate of ash sintering is governed by the ratio of glassy material to crystalline species and the viscosity of the glassy phase.

ACKNOWLEDGEMENT

The work was carried out at the Central Electricity Research Laboratories and the paper is published by permission of the Central Electricity Generating Board.

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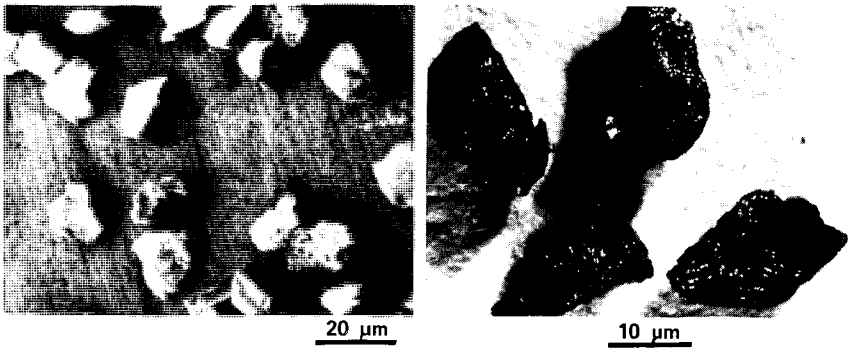


(a) ADVENTITIOUS (b) INHERENT-WHITE PARTICLES

FIG. 1 MINERAL MATTER IN COAL

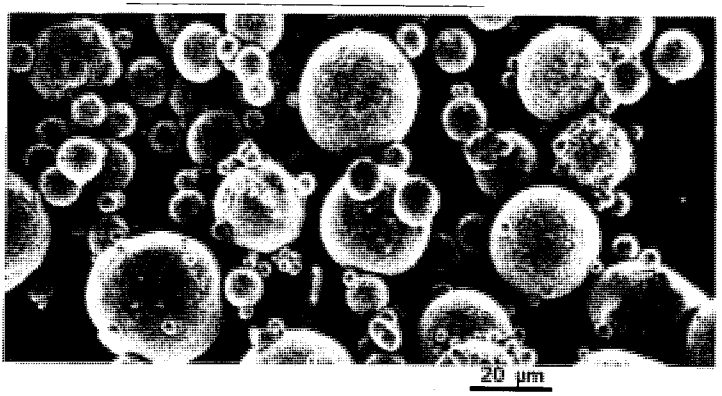


FIG. 2 PULVERIZED COAL ASH

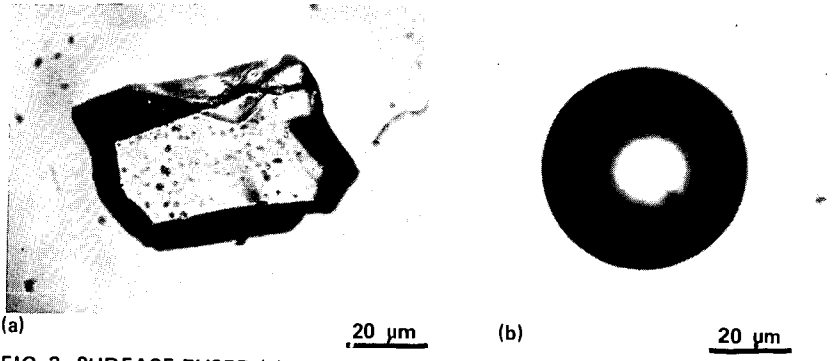


FIG. 3 SURFACE FUSED (a) AND SPHERIDIZED (b) SILICATE PARTICLES

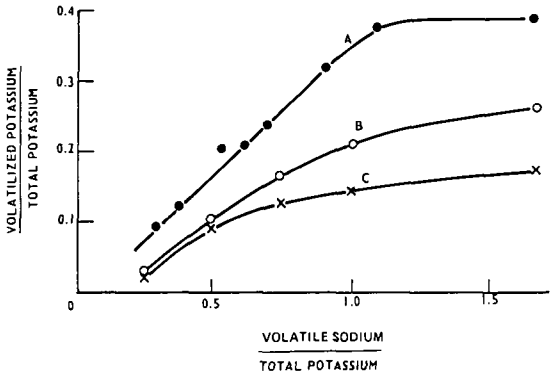


FIG.4 THE EFFECT OF SODIUM CHLORIDE ON RELEASE POTASSIUM FROM SILICATES

A – COAL SILICATES
B – MUSCOVITE
C – ORTHOCLASE

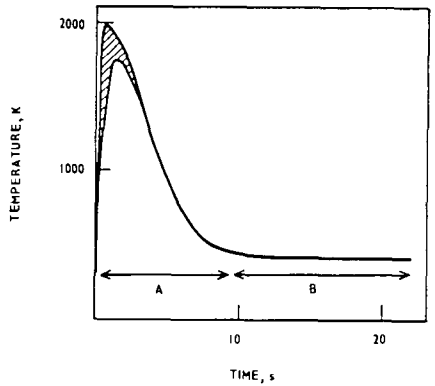
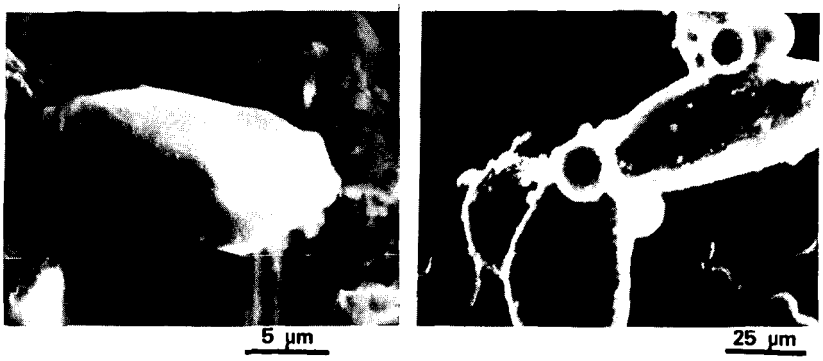


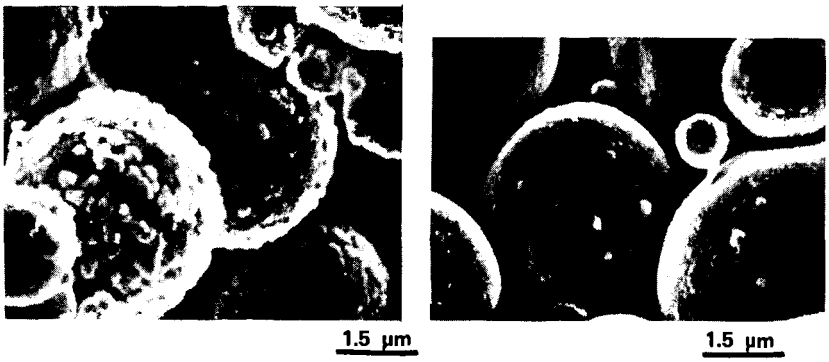
FIG.5 TEMPERATURE/TIME PLOT FOR ASH PARTICLES IN A 500 MW PULVERIZED COAL FIRED BOILER – 0.1 μm (TOP CURVE) TO 100 μm (LOWER CURVE) SIZES

SECTION A COMBUSTION AND HEAT EXCHANGE CHAMBERS
SECTION B ELECTRICAL PRECIPITATORS AND CHIMNEY



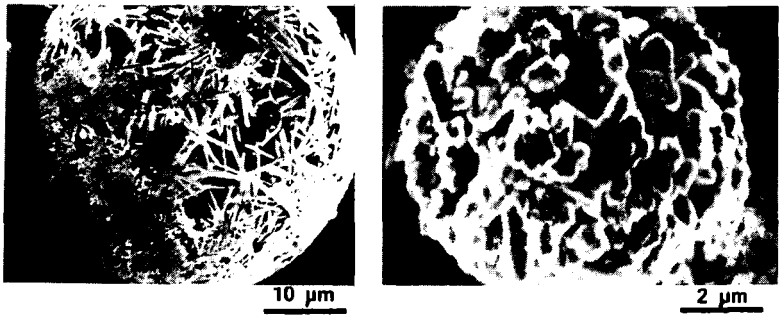
(a) UNFUSED QUARTZ PARTICLE

(b) ELONGATED SILICATE PARTICLES



(c) MICROIDS ON ASH

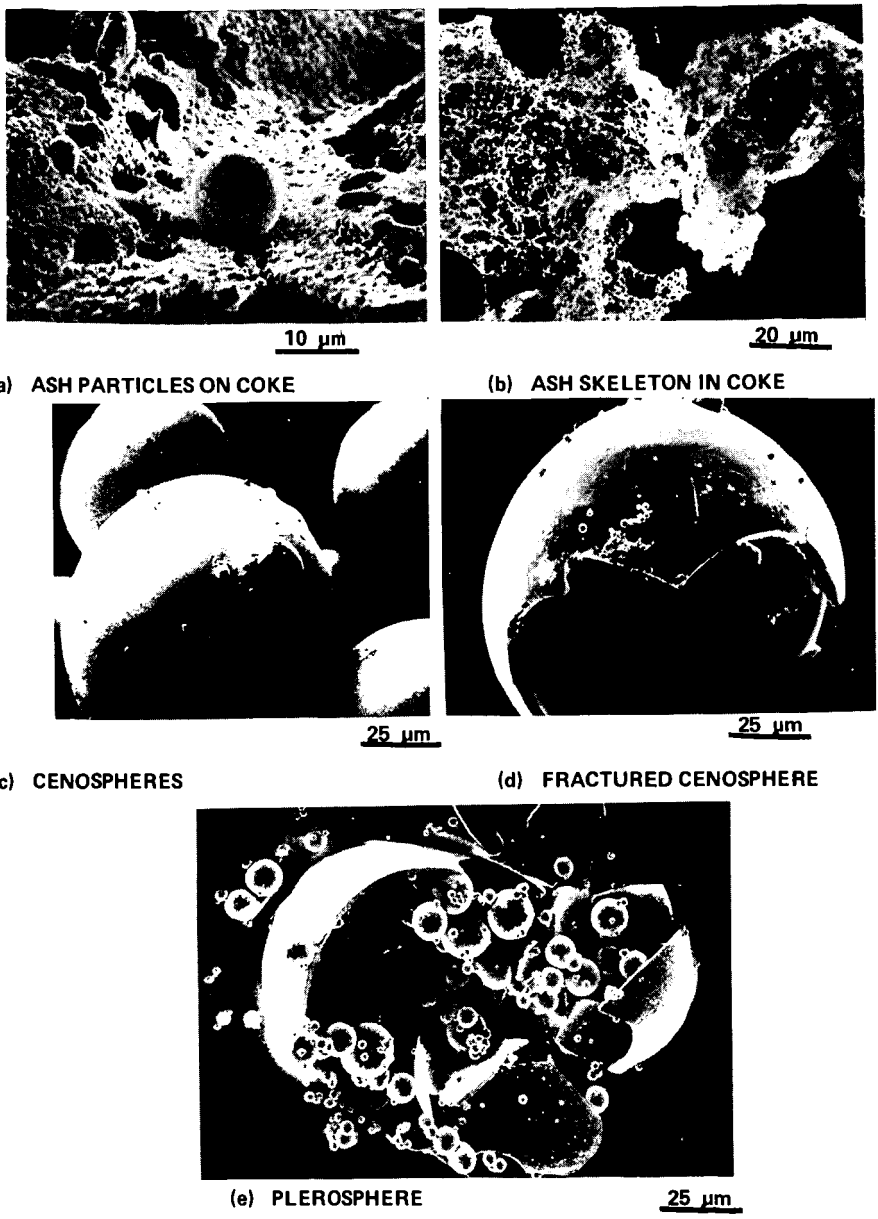
(d) ACID CLEANED ASH



(e) MULLITE NEEDLES IN ASH

(f) QUARTZ CRYSTALLOIDS

FIG. 6 DIAGNOSTIC FEATURES OF FLAME HEATED ASH



(a) ASH PARTICLES ON COKE

(b) ASH SKELETON IN COKE

(c) CENOSPHERES

(d) FRACTURED CENOSPHERE

(e) PLEROSPHERE

FIG. 7 COALESCENCE PRODUCTS OF INHERENT ASH IN FLAME

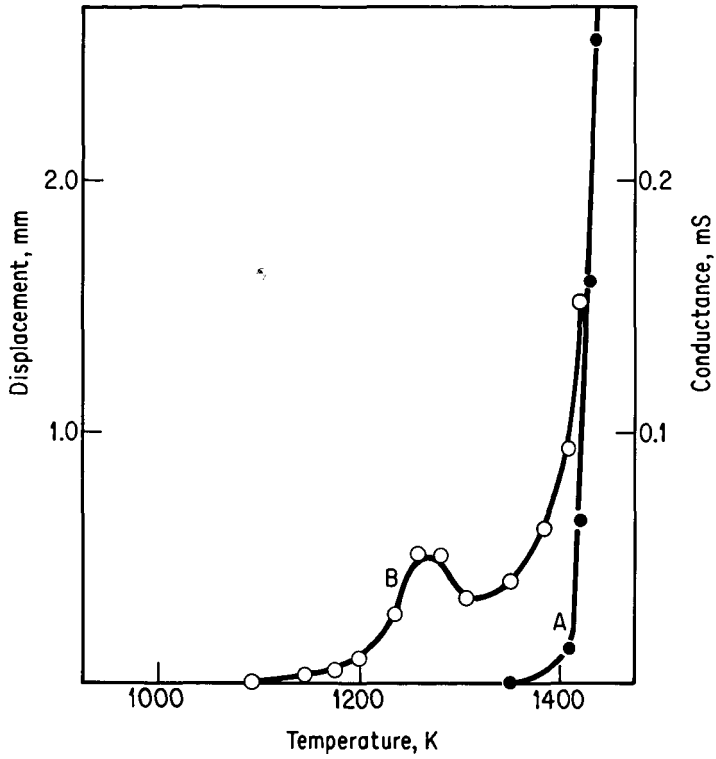


FIG. 8 SIMULTANEOUS SHRINKAGE AND CONDUCTANCE MEASUREMENTS LEIGH CREEK (AUSTRALIA) COAL ASH

A – SHRINKAGE
B – CONDUCTANCE