# Particle Impact Erosion and Abrasion Wear – Predictive Methods and Remedial Measures

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by

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# EXECUTIVE SUMMARY

## Objectives

The overall objectives of the project can be listed as follows;

- To select a suite of test coals that is representative of the range of ash contents and ash qualities normally encountered in steam coals worldwide, and to subject these coals to a programme of basic characterisation work using both conventional laboratory techniques and Computer Controlled Scanning Electron Microscopic (CCSEM) techniques.

- To measure the rate of abrasive wear of coal mill grinding elements associated with the milling of these coals, using the Mini-mill Test Facility operated by Mitsui Babcock in Renfrew.

- To measure the rate of erosive wear associated with the impact of pulverised coal particles made from these coals on a carbon steel target, under controlled conditions, using the Erosion Test Rig operated by Mitsui Babcock in Renfrew.

- To measure the relative erosion resistance of a range of target materials, including a number of specialist coatings.

- To develop correlations between the abrasion and erosion characteristics of the test coals and the ash characteristics of the coals, measured using CCSEM techniques.

## Summary

This project involved a detailed investigation of the abrasion and erosion characteristics of a suite of pulverised coals, selected to represent the full range of coal quality encountered by boiler plant designers and operators worldwide, and of the relative erosion resistance of a range of materials. The principal objective of the abrasion and erosion work was to develop improved correlations between the abrasion and erosion behaviour of the coals and their basic characteristics, as measured using CCSEM techniques. The CCSEM techniques are relatively novel, and generate quantitative information about the chemical and microstructural characteristics of the pulverised coals, which is not available by any other technique.

The abrasion and erosion testwork and the CCSEM characterisation of the test coals have been very successful, and very good correlations have been developed between the measured abrasion and erosion rates and the volume percent of hard mineral particles above a certain size in the pulverised coals. These correlations are suitable for predictive purposes, and the work has resulted in the development of laboratory procedures suitable for the assessment of the abrasion and erosion behaviour of unfamiliar coals. This represents a very significant step forward in our understanding of the abrasion and erosion behaviour of coal particles.

The project also involved the measurement of the relative erosion resistance of a range of materials and coatings, relevant to the materials of construction of the components of coal milling and combustion equipment and of boiler plant.

## Cost

The cost of the project was £240,000, of which £120,000 was provided by the Department of Trade and Industry and £120,000 by the project partners.

## Duration

24 months – December 2000 to December 2002

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## Background

Erosive and abrasive wear of the components of the fuel handling and firing systems, and of the boiler, are major issues for the designers and operators of coal-fired power plants (Raask 1988, EPRI 1985). The wear mechanism in both cases is almost entirely due to the presence of hard mineral matter in coals, and principally quartz and pyrite, these materials being harder than steels. The carbonaceous matter and clay minerals are relatively soft and cause little erosive or abrasive wear.

**Abrasive wear** is caused by the sliding of hard particles over a surface, or between two surfaces. In power plants, the main areas of concern are in coal handling, crushing and milling equipment, where abrasive wear of metal components in contact with the mineral constituents of the coal can affect the performance of the equipment, and can be a significant contributor to the maintenance costs.
**Erosive wear** is associated with the impact of hard particles, carried in a fluid at significant impact velocities, on metallic and other surfaces. The key areas of concern in coal-fired power plant are the internal surfaces of coal mills, the pulverised coal pipework, and the burner internals, where erosive wear due to the impact of pulverised coal particles can have an effect on the performance of items of equipment, and can increase plant maintenance costs. Erosive wear of boiler tubes and other surfaces in the convective section, either by ash impact erosion or due to the action of the sootblowers, is also of concern.

Knowledge of expected abrasion and erosion wear rates for particular coals is necessary to allow equipment suppliers to design for the intended fuel and provide guarantees of equipment lifetimes, and to allow operators to plan maintenance schedules. This is particularly important in the case of power plants that utilise high ash coals, where the costs of abrasive and erosive wear can be very significant.

## Experimental work

The experimental approach adopted for this project involved the use of two small-scale test facilities, viz:

- The Mini-mill Test Facility, which is operated by Mitsui Babcock in Renfrew, is a small-scale coal mill, which operates at a raw coal throughput of 5 kg $h^{-1}$, and which permits direct measurement of the weight losses of the coal grinding elements due to abrasive wear. The Mini-mill product was then employed as the feed material for the Erosion Rig experiments, and to provide samples of pulverised coal for the CCSEM work.

- The Erosion Rig, which is also operated by Mitsui Babcock in Renfrew, is a small-scale test facility, in which particles of the erodent material, entrained in a stream of air at a controlled velocity, can be directed at a small target coupon under controlled conditions. The weight loss of the target coupon due to erosive wear is measured, and the results are normally expressed in terms of the weight loss in milligrams per kg of erodent material.

The CCSEM characterisation, carried out at Imperial College, was performed on both the raw coal samples, and on samples of the pulverised coal product material from the Mini-mill tests. For the quantitative work, small samples of the pulverised coals were taken, and these were mixed with an iodoform-doped epoxy resin, in such a way as to provide an even distribution of the pulverised coal particles through the resin matrix. The iodoform doping technique is used to provide contrast between the resin and the carbonaceous matter in the coal, when viewed using back-scattered electron imaging in the SEM and to allow the resin matrix to be differentiated chemically from the coal substance. After setting, the mounted specimens were ground and polished to a 0.25 μm finish to provide a random plane cut through the suspended particles. The pulverised coal specimens were examined in a JEOL 6400 SEM, and the mineral matter was analysed using the CCSEM, enabling automated energy dispersive spectrometry (EDS) chemical analysis using ZAF and PROZA corrections to be performed on hundreds of particles of inorganic matter. Analysis of the data provided details of the types and quantities of minerals present in each specimen, and information on the sizes and shapes of individual occurrences of particular mineral types.

## Results

One of the principal objectives of the work was to develop improved correlations between the measured abrasion and erosion behaviour of the coals and their ash characteristics, as determined using the CCSEM techniques. It has been found that both the abrasion and erosion characteristics of the coals can be attributed to the relatively small quantities of hard mineral particles present in the coals. More specifically, the abrasion and erosion characteristics of the coals are controlled by the total quantity of these mineral species that are greater than 25 μm in diameter and that are liberated or excluded, i.e. which are not included within larger particles either of coal substance or of the clay minerals, which tend to be the most abundant constituents of the coals.

Very good linear correlations have been obtained between the measured abrasion and erosion rates for the test coals and the total quantities of the larger, hard, excluded mineral particles that the coals contain, expressed as a volume percentage. This type of quantitative information on the mineral characteristics of the coals can only be obtained by CCSEM techniques.

The work on the erosion behaviour of samples of pulverised coal ash, produced by combustion of two of the test coals in the Combustion Test Rig, operated by PowerGen at Ratcliffe, indicated that the overall effect of the mineral transformations in the flame was to increase the erosiveness of the fly ash materials compared to that of the original mineral material. It was also noted that the erosive behaviour of the two fly ashes was fairly similar. These findings provide further evidence that the erosion of heat exchange tubes in the convective sections of the boiler is controlled largely by the ash particle concentration and by the local gas velocities, and that the differences between the ash characteristics is likely to be a second order effect in most cases.

The work on the relative erosion resistance of a range of materials has indicated that the normal steels employed for boiler tubes and other components have very similar erosion wear rates when impacted with pulverised coal particles at controlled velocities. The harder ferrous metals, like the high chrome cast irons, can provide a 2-3 times reduction in the erosion rates and, for this reason, these materials have been employed for the construction of the components at burner inlets, where erosion wear associated with concentrated streams of pulverised coal particles is a common problem. The results with the specialised coatings indicated that reductions in erosion wear rates by up to a factor of ten were measured for the tungsten carbide and chromium carbide coatings. The employment of coatings of this type should be given serious consideration for relatively small components, which may be subject to severely erosive conditions, and where a compelling economic case for their use can be made.

## Conclusions

The results of this project represent a significant step forward in this subject area, in that they confirm, in a compelling fashion, that the erosion and abrasion behaviour of coals is controlled principally by the hard mineral particles, and more specifically those hard particles above 25 microns in size that are not contained within larger particles of coal or clay mineral. This has been suspected for some time, however it is only the availability of suitable quantitative information on the size and distribution of the particles from CCSEM analysis that has allowed suitable correlations to be developed.

The results of the project provide the industry with a means of the prediction of the abrasion and erosion behaviour of unfamiliar coals. This is of value both to the suppliers of coal milling and combustion equipment, who have to provide guarantees of component life, and to the operators of coal-fired power plants in the development of coal purchasing strategies and maintenance schedules. It is anticipated that these results will be of direct value to the project partners, and principally to the industrial partners, Mitsui Babcock and PowerGen, who both have commercial interests in the abrasion and erosion behaviour of coals and the impact of abrasive and erosive wear on the performance and integrity of coal processing plant.

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# 1. INTRODUCTION

Erosive and abrasive wear of the components in the fuel handling and firing systems, and in the boiler, are major issues for the designers and operators of coal-fired power plant (Raask 1988, EPRI 1985). The wear mechanism in both cases is almost entirely due to the presence of hard mineral matter in coals, and principally quartz and pyrite, these materials being harder than steels. The carbonaceous matter and clay minerals are relatively soft and hence cause little erosive or abrasive wear.

**Abrasive wear** is caused by the sliding of hard particles over a surface, or between two surfaces. In power plants, the main areas of concern are in coal handling, crushing and milling equipment, where abrasive wear of metal components in contact with the mineral constituents of the coal can affect the performance of the equipment, and can be a significant contributor to the maintenance costs.

**Erosive wear** is associated with the impact of hard particles, carried in a fluid at significant impact velocities, on metallic and other surfaces. The key areas of concern in coal-fired power plant are the internal surfaces of coal mills, the pulverised coal pipework, and the burner internals, where erosive wear due to the impact of pulverised coal particles can have an effect on the performance of items of equipment, and can increase plant maintenance costs. Erosive wear of boiler tubes and other surfaces in the convective section, either by ash impact erosion or due to the action of the sootblowers, is also of concern.

Knowledge of expected abrasive and erosive wear rates for particular coals is necessary to allow equipment suppliers to design for the intended fuel and provide guarantees of equipment lifetimes, and to allow operators to plan maintenance schedules. This is particularly important in the case of power plants that utilise high ash coals, where the costs of abrasive and erosive wear can be very significant.

The current project is a collaborative effort involving four partners, viz:

- **Mitsui Babcock**, who acted as Project Co-ordinator and who were responsible for the programmes of coal testing, and the erosion and abrasion testwork,

- **The Department of Materials, Imperial College**, who were responsible principally for the detailed, quantitative mineralogical analysis of the test coals using a Computer Controlled Scanning Electron Microscopy (CCSEM) technique,

- **Plasma and Thermal Coatings Ltd**, who provided specialist technical advice on coatings for erosion resistance, and provided specimens of coatings for erosion testing, and

- **PowerGen**, who provided specialist technical support, and assistance with the selection and the procurement of appropriate samples of the test coals.

The project work programme was carried out over a two-year period, and involved the following activities:

- Coal selection, sample preparation and characterisation, using both conventional and CCSEM techniques,
- Abrasion testwork, relevant to the behaviour of coals in vertical spindle mills, with the relative abrasion rates of the grinding elements associated with the test coals being measured experimentally using the Mini-mill Test Facility, which is operated by Mitsui Babcock in Renfrew,
- Erosion testwork, on both pulverised coal and fly ash particles, and investigating a range of target materials and coatings, with the relative erosion rates being measured using the Erosion Test Facility, which is operated by Mitsui Babcock in Renfrew.

The results of the experimental work have been described in a series of specific reports. This document presents a summary of the major findings of the work, and a description of the work done on the development of correlations between the relative abrasion and erosion behaviour of the test coals, and their mineralogical characteristics, as measured using CCSEM techniques.

## 2 THE SELECTION AND CHARACTERISATION OF THE TEST COALS

The choice of the test coals was based on the following criteria:

- To provide a range of steam coal ash contents and ash chemistries representative of that normally encountered by equipment suppliers and plant operators, worldwide.
- The coals selected were also of interest to the project partners, i.e. indigenous British coals, coals traded on the world steam coal market, and the very high ash coals indigenous to the Indian subcontinent.

A total of thirteen coals were selected for the test programme, and these are listed below:

### Indigenous British coals

| | |
|---|---|
| Rossington | A large sample of this British deep-mined coal was obtained a number of years ago, and this is employed as one of the standard coals for Mini-mill testwork. |
| Harworth | This is a fairly typical high-sulphur, high pyrite British power station coal. |
| Oxcroft | Also high in sulphur and pyrite, this coal is from a British opencast mine. |

### Indigenous Indian Coals

These coals have ash contents in excess of 30%, and are associated with severe erosion and abrasion problems in Indian power stations.

Samples were delivered from the following five stations:

- Talcher, is a large coal-fired power station in Orissa, on the eastern side of India, with the principal coal supplies coming from the Lingraj and Jaannath mines.
- Bakreswar, is a large, newly-built, coal-fired power station in West Bengal,
- Rihand, a large, coal-fired power station in Uttar Pradesh, with the principal coal supplies coming from the Amiohri/Dudhichua mine
- Satpura is a large coal-fired power plant located in Madhya Pradesh, and
- Koradi is a large coal-fired power plant located near Nagpur, Maharashtra, in Central India.

**North American Coals**

| | |
|---|---|
| Powder River Basin | A sub bituminous Western coal from the USA, widely used for power generation in North America, and which is currently being imported into Europe. |
| Bailey | A North American export bituminous, steam coal. |

**World traded steam coals**

| | |
|---|---|
| Hunter Valley | An export steam coal from Australia. |
| Rietspruit | An export steam coal from South Africa. |
| La Loma | An export steam coal from Colombia, with a relatively low ash content. |

Laboratory samples were prepared from each of the delivered coal samples, and the following basic analysis procedures were carried out on each. The analysis procedures are described in BS 1016.

Proximate analysis

Forms of sulphur

Ash analysis

Hardgrove Grindability Index and Abrasion Index

The analysis data for all of the test coals are listed in Table 1. It is apparent from the proximate analysis data that the ash contents of the test coals, on a dry basis, are in the range 5.1% to 49.1%. These values are reasonably representative of the range of ash contents of steam coals, commonly encountered on a worldwide basis.

Estimates of the quartz and pyrite contents of the test coals are also presented in Table 1. The quartz contents were calculated from the ash analysis data using the following simple equation (Raask, 1988):

$$\text{Quartz content of the ash (\%)} = SiO_2 - 1.5\ Al_2O_3,$$

Where $SiO_2$ and $Al_2O_3$ are the wt.% silica and alumina in the ash.

The pyrite contents of the coals and ashes were calculated directly from the measured pyritic sulphur contents.

A detailed description of the results of the coal characterisation work is presented in Mitsui Babcock Technology Report No. 62/02/002, from which Table 1 is taken.

## 3. THE ABRASIVE WEAR OF THE GRINDING ELEMENTS OF VERTICAL SPINDLE, BALL AND RACE, COAL MILLS

The grinding elements of all types of coal mill are subject to abrasive wear. For vertical spindle ball and ring mills, the abrasive wear is caused, in the main, by two principal mechanisms, viz:

- Metal to metal contact between the grinding ball and rings, for instance during mill start-ups and shutdowns,
- Abrasive wear of the balls and rings due to the sliding contact between the grinding element surfaces and hard mineral particles in the coal being milled, during normal operation.

The evidence from plant experience indicates that, to a first approximation, the abrasion rate of mill grinding elements is dependent on the ash contents of the coals being fired. Mill component abrasion rates are very much higher in power plants in India and South Africa, for instance, where indigenous coals with very high ash contents are fired in power plant boilers, than in plants in most other countries, which fire lower ash coals.

This point can be illustrated by plotting the measured Abrasion Index values for a range of world steam coals against their ash contents, on a dry basis. A plot of this type has been reproduced in Figure 1, which is based on data collected by Mitsui Babcock over a number of years, for a range of world steam coals. It is apparent from these data that, although the Abrasion Index values clearly increase with increasing ash content, the linear correlation is not good enough for predictive purposes, and a more advanced approach to understanding the abrasion behaviour of steam coals is required.

This was one of the principal objectives of the work done within the current project. The abrasion rates of a suite of coals have been measured using the Mini-mill Test Facility operated by Mitsui Babcock in Renfrew. The results have been correlated with a number of coal quality parameters, including those measured by CCSEM techniques, in an attempt to gain a better understanding of the abrasion process and to develop correlations that are useful for predictive purposes.

## 3.1 The Mini-Mill Test Facility

A schematic diagram of the Mini-mill test facility is reproduced in Figure 2, and a more detailed sketch of the mill assembly is presented in Figure 3. The Mini-mill is a fully functional 0.34 E10 mill, fitted with a static classifier. The dimensions of the grinding elements are:

| | |
|---|---|
| Balls | 25.4 mm diameter, and |
| Track | 86.3 mm diameter. |

The load to the grinding elements is applied externally by springs located on the outside of the mill body.

The mill is fed by means of a vibratory screw feeder. The Mini-mill feed rate for a standard test is 5 kg $h^{-1}$, and around 20 kg of feed is required for a test. The test material is normally air dried, and then crushed and screened to a top size of 1.6 mm, with any oversize material being crushed and recycled.

The feed material passes from the screw feeder down the feed pipe and on to the mill table. It then passes through the grinding elements and is picked up by the air at the throat. The coal is then carried to the classifier. The fine coal particles pass through the classifier and exit the mill. The oversize material is returned to the mill table. The mill product is collected in a high efficiency cyclone, followed by a bag filter with an aperture of 1 μm. The mill is operated under suction, and the airflow rate is measured after the bag filter. The mill operates at ambient temperature.

The Mini-mill is powered by a SEW helical/worm-geared motor unit with a nominal speed of 200 rpm. A torque transducer is mounted on the mill drive shaft to provide direct measurement of the torque and the rotational speed of the drive shaft. From these values, the mill power consumption is calculated.

The standard Mini-mill test conditions are listed below. Testing under these conditions allows comparison of the test data with those of a range of fuels in the Mini-mill database.

| | |
|---|---|
| Test time | 150 minutes |
| Mill speed | 200 rpm |
| Coal feed rate | 5 kg $h^{-1}$ |
| Load applied to grinding elements | 59 kg |

Scavenging air flow rate 0.225 $m^3$ $min^{-1}$

On completion of the test run, the particle size distributions of both the feed materials and the mill products are measured by dry sieving and by using a laser light scattering technique for coal particle diameters in the range 300-2.4 μm. The surface areas of the feed materials and the products are calculated from the size distribution data, and the new surface area produced during the milling process is calculated by difference.

The principal parameters that are measured during a Mini-mill test are:

- The feed and mill product size distributions and surface areas,
- The new surface area produced by milling,
- The mill power consumption, and
- The individual ball and ring metal losses due to abrasive wear during the test.

### 3.2 The Mini Mill Abrasion Data

Ten of the coals listed in Section 2 above were tested in the Mini-mill Test Facility, and the results are presented in Table 2. The measured total Mini-mill abrasion rates for the different coals vary in the range 8-92 mg $kg^{-1}$ of coal milled. These values have been plotted against the ash contents of the coals, on a dry basis, in Figure 4. Again, although a clear trend is apparent, with the measured Mini-mill abrasion rates increasing with increasing ash contents of the coals, the correlation is not suitable for predictive purposes. There are a number of coals that do not obey the correlation particularly well, and it is clear that the abrasion characteristics of the ash materials in the different coals vary significantly.

It is known, for instance, that only relatively small proportions of the ash contents of most coals consist of materials that are significantly harder than steel, and can contribute to the abrasive wear of mill grinding elements. The coal substance, and the clay minerals, which comprise the greater part of the ash content of most coals, are both relatively soft, and do not contribute significantly to abrasive wear.

The relative hardness values (Moh's scale) of the more abundant coal minerals and of mild steel are listed in Table 3. In most coals, the more important hard mineral species are quartz ($SiO_2$), and pyrite ($FeS_2$), which are significant mineral components of many coals. Other hard minerals, which can be significant in some high ash coals, include feldspars and garnets.

The importance of the quartz and pyrite has been recognised previously, and a number of simple, empirical Abrasion Indices are based on the quartz and pyrite contents of coals, calculated from the ash analysis data, see for instance Raask, (1988), and a number of the references cited therein.

The Mini-mill abrasion data were plotted against a number of these indices, however the correlations obtained did not provide any significant improvement over the correlation obtained with the ash contents of the coals.

It is clear that a more advanced approach to coal ash characterisation is required to provide a better understanding of the abrasion behaviour of coals. One of the key objectives of the project was to make use of the coal ash characterisation data, available from CCSEM techniques, to provide improved correlations and a better understanding of coal abrasion characteristics. The results of this work are described in Section 5 below.

## 4. THE EROSION BEHAVIOUR OF COAL AND ASH PARTICLES AND THE EROSION RESISTANCE OF MATERIALS

### 4.1 The Erosion Behaviour of Pulverised Coal Particles

This section of the report is concerned with the results of erosion rig tests on a number of samples of pulverised coal and pulverised coal fly ash. A total of ten pulverised coal samples have been tested and these were selected to provide a range of ash contents from 6.4-44.4%, as received, which represents the range of values normally encountered in steam coals worldwide.

The samples of pulverised coal were prepared by milling the raw coals in the Mini-mill Test Facility at Mitsui Babcock Technology in Renfrew, Scotland. Erosion rig experiments were also carried out using a bulk sample of pulverised coal from Mao Khe in Vietnam, which was the standard erodent used for the tests on wear-resistant materials, described in Section 4.3. This erodent material was employed for this work because a very large sample of pulverised coal, in excess of 200 kg, was required.

The erosion testwork was performed on the Erosion Test Rig operated by Mitsui Babcock Technology in Renfrew. The erosion rates of carbon steel targets, for each of the test pulverised coals, were measured at a range of impact velocities from 35 to 65 m $s^{-1}$ and at an impact angle of 45 degrees. Under these test conditions, the erosion rates, expressed as mg of metal loss from the target coupon per kg of pulverised coal, were measured.

A schematic diagram of the Erosion Test Rig is shown in Figure 5. The main components of the rig are:

- The feed hopper and vibratory feeder,
- The vertical accelerating tube,
- The specimen chamber and specimen holder,
- The cyclone and filter, and
- The control valve, air pump and rotameter.

The air pump draws air, at a controlled velocity, down the vertical accelerating tube into the specimen chamber. The erodent particles are fed from a feed hopper, via a vibrating chute to the top of the vertical accelerating tube, and are entrained in the air stream. The erodent feed rate can be controlled by altering the motor speed on the vibrating hopper and chute.

The erodent particles are directed towards the target specimen, which is clamped in a holder in the specimen chamber at the required impact angle. After striking the specimen, the erodent particles are drawn by the air out of the specimen chamber and are collected in the cyclone and back-up filter. The clean air is then drawn through the flow-regulating valve and is exhausted to atmosphere through the flow rate indicator.

An Erosion Test Rig experiment normally involves exposure of the test specimen to a controlled mass of erodent particles, at controlled impact velocity and angle. The result of a test is obtained by post-test examination of the specimen, with the weight loss due to erosive wear being the most readily measured parameter. The erosion rate is commonly expressed in terms of the weight loss from the target per unit mass of erodent material. It is also possible to examine the microstructure of the eroded scar on the surface of target coupon, and this can provide information on the erosion wear mechanism.

In general terms, the relationship between the erosive wear rate and the particle impact velocity can be described by a simple power law equation:

$$W = a\, v^n,$$

Where:

$W$ is the measured erosion wear rate in mg $kg^{-1}$ of erodent,

$a$ is a constant,

$v$ is the particle impact velocity, and

$n$ is the velocity exponent.

The results of the erosion rig experiments on the pulverised coal samples are listed in Table 4. The measured velocity exponents for the pulverised coal samples varied between 1.69 and 3.15 for the ten pulverised coal samples, with the majority being between 2 and 3. This finding is generally in line with velocity exponents for the erosion of steel targets with a range of erodents, however the relatively wide range of values reflects the rather complex, multi-component nature of pulverised coal particles as erodents.

The measured erosion rates for the pulverised coal samples, at an impact velocity of 40 m $s^{-1}$, were in the range 0.47-5.26 mg $kg^{-1}$ of coal. In general terms, there is a trend of increasing erosion rate with increasing ash content of the coal. These results are similar in many ways to the mill abrasion results presented in Figure 4 and, again, the linear correlation with the ash contents of the coals is relatively poor. As with the Mini-mill abrasion data, described above, attempts to derive correlations using the empirical erosion indices, based on the calculated quartz and pyrite contents of the coals, did not provide any improvement over the correlation with the ash content alone.

Again, it is clear that a more advanced approach to coal ash characterisation is required to provide a better understanding of the abrasion behaviour of coals. One of the key objectives of the project was to make use of the coal ash characterisation data, available from CCSEM techniques, to provide improved correlations and a better understanding of the coal particle impact erosion process. The results of this work are described in Section 5, below.

## 4.2 The Erosion Behaviour of Pulverised Coal Fly Ash Particles

In the case of two of the test coals, Hunter Valley and Bailey, samples of pulverised fuel ash were available from combustion testwork that had been conducted previously on the Combustion Test Rig at Ratcliffe, operated by PowerGen.

The characteristics of the fly ashes from pulverised coal combustion are very well understood, (see for instance Raask, 1988 and the references cited therein), and the results of the CCSEM analysis of the Hunter Valley and Bailey fly ashes were fairly familiar. The majority of the particles are small, glassy alumino-silicate spheres and fused, spherical pyrite residues of up to around 50μm in diameter. Very few free quartz particles were detected, none in the Bailey ash and less than 1% by weight in the Hunter Valley ash.

The erosion behaviour of these samples with a carbon steel target, at an impact angle of 45° and over a range of impact velocities, has been measured in the Erosion Test Rig. The erosion rate-velocity plots for these samples are reproduced on a log-log scale in Figure 6. Very good linear correlations were obtained in both cases, and the two lines are almost parallel, with slopes or velocity exponents of 2.65 and 2.61 for the Hunter Valley and Bailey ashes, respectively.

A comparison of the measured erosion rates for the Hunter Valley and Bailey pulverised coals and the corresponding fly ash samples, at an impact velocity of 40 m $s^{-1}$, is presented in Table 5. These data indicate that the fly ash materials were significantly more erosive than the mineral material present in the pulverised coal.

The data presented in Table 5 indicate that the overall effect of the mineral transformations in the flame, and principally the fusion of the clay mineral particles to form glassy spheres, is to increase the erosiveness of the fly ash materials compared to that of the original mineral material in the coal.

## 4.3 The Erosion Resistance of Coatings and Other Materials

The rates of wear of a range of materials, subject to pulverised coal particle impaction, have been measured under standardised conditions in the Erosion Test Rig in Renfrew, operated by Mitsui Babcock The test erodent was a high ash anthracitic coal from Vietnam, milled to the appropriate fineness. The test conditions were:

| | |
|---|---|
| Particle impact velocity | 50 m $s^{-1}$ |
| Angle of impact | 45° |

Full erosion wear-erodent mass curves for each test material were measured. The test materials were:

- Carbon steel,
- 25% Cr cast iron, hardened and tempered, and

four specialist coating materials supplied by Plasma and Thermal Coatings Ltd, viz:

- Ni/Cr 80/20,
- Stellite 6,
- 80/20 CrC/NiCr, and
- WC/12% Co.

In the original programme for the project it had been proposed that the relative erosion of a number of boiler tube materials would be studied in the Erosion Test Rig. It became apparent, however, in the course of the initial literature search that this work has largely been done. Raask (1988), for instance, has provided a plot of the erosion rate against the Vickers Hardness for a wide range of steels, on a log-log scale, that indicates a very good negative linear correlation between these parameters. This correlation has been reproduced in Figure 7.

The Vickers Hardness values for the steels normally employed for boiler tubes, including ferritic, martensitic and austenitic types, are in a relatively narrow range between 150 and 200. This indicates that the relative erosion rates for these materials also lie within a very narrow range, similar to that measured for the carbon steel reference material that was used in the current work. It was decided, therefore to concentrate the work on a range of coating materials, which provide a wider range of erosion resistance behaviour.

The erosion rates of the materials listed above were characterised by the slopes of the measured erosion weight loss-erodent mass curves, and were expressed in mg per kg of erodent. The results are reproduced in Table 6.

The carbon steel, and the Stellite 6 and 80/20 NiCr coatings, exhibited very similar erosion rates, at around 2-3 mg $kg^{-1}$, under the test conditions. These coatings are applied largely for protection against corrosive attack, and do not provide a high level of protection against particle impact erosion.

The measured erosion rate for the 25% Cr cast iron was lower than for the carbon steel, as expected, by a factor of around 3. The tungsten carbide and chromium carbide coatings had significantly lower erosion rates compared to carbon steel under the test conditions, by factors around 10 in volume terms. These materials do provide significantly lower erosion rates than carbon steel, and the results of a series of experiments at different impact angles have indicated that this improvement in erosion resistance applies at all impact angles up to 90°.

It may be appropriate to consider the use of the carbide coatings in particularly aggressive conditions, in situations for which a compelling economic case can be made.

## 5. THE SEM AND CCSEM ANALYSIS OF THE RAW AND PULVERISED COAL SAMPLES

The coal samples for SEM and CCSEM analysis were supplied in two forms, viz:

- As raw coal, typically in pieces from 1-2 mm to 2-3 cm in size, and
- As pulverised coal, produced by processing in the Mini-mill Test Facility operated by Mitsui Babcock in Renfrew, and which has a topsize of around 300 μm.

The raw coal samples were sorted by hand, and twelve pieces of coal, which had a high mineral matter content, were selected from each coal for qualitative characterisation in the scanning electron microscope. This procedure provided general information about the nature and the distribution of the mineral material in the test coals.

Small samples of the pulverised coals, prepared from the ten test coals in the Mini-mill, were taken, and these were mixed with an iodoform-doped epoxy resin, in such a way as to provide an even distribution of the pulverised coal particles through the resin matrix. The iodoform doping technique is used to provide contrast between the resin and the carbonaceous matter in the coal, when viewed using back-scattered electron imaging in the SEM. After setting, the mounted specimens were ground and polished to a 0.25 μm finish to provide a random plane cut through the suspended particles.

The pulverised coal specimens were examined in a JEOL 6400 SEM, and the mineral matter was analysed using CCSEM techniques, including automated energy dispersive spectrometry (EDS) chemical analysis using ZAF and PROZA corrections, on hundreds of particles of inorganic matter. Analysis of the data provided details of the types and quantities of minerals present in each specimen.

The following major mineral species were identified in the test coals:

- The clay minerals, designated either illitic clays (potassium rich alumino-silicates) or kaolinite (potassium poor alumino-silicates), as major components of most of the coals,

- Quartz (silica rich), as a significant component of most of the coals,

- Pyrite (iron and sulphur rich) and siderite (iron rich, sulphur poor) as significant components of most of the coals,

- Calcite, dolomite and apatite as components of some of the coals, and

- Alkali feldspars and garnets, as components of some of the Indian coals.

The CCSEM analysis provides quantitative information about the following mineral matter characteristics of the test coals:

- The quantities of the various mineral species, which can be expressed either in terms of a volume or mass percentage,

- The size distribution of the individual mineral occurrences, normally expressed as the diameter of a circle with the same area as the analysed cross section,

- The shape of individual mineral occurrences, normally expressed in terms of the aspect ratio of the particle cross section,

- Information about the degree of inclusion of the mineral species, within coal particles or other mineral particles, can also be provided. The conventional definition of ‘included’ mineral matter for CCSEM analysis is that >10% of the perimeter of the mineral occurrence is adjacent to coal substance. For this work, however, a further category was defined, i.e. a ‘contained’ mineral occurrence has >90% of its perimeter adjacent to coal substance. It is assumed that mineral material occurrences ‘contained’ within coal particles do not contribute significantly to the abrasive or erosive behaviour of the pulverised coal.

The relevant mineral characteristics, derived by CCSEM analysis, of the test pulverised coal samples are listed in Tables 7 to 10. It is clear from these data that there are very significant differences in the quantities and characteristics of the hard mineral species in the test coals, and particularly in the proportions of the minerals contained within coal particles and their size distributions. The relevance of these findings will be described in detail in the next Section of this report.

## 6. CORRELATING THE CCSEM PULVERISED COAL DATA WITH THE ABRASION AND EROSION PROPERTIES OF THE COALS

The CCSEM technique provides a wealth of data about the characteristics and associations of the mineral material in the coals, and in order to provide meaningful correlations with the measured Mini-mill abrasion data and the measured erosion rate data for the test coals a number of simplifying assumptions have to be made, viz:

- It has been reported previously that the abrasiveness and erosiveness of a coal are linked to those components of the coal that are harder than steels. For the great majority of coals, the relevant hard mineral species are quartz and pyrite, however the results of the CCSEM analysis presented above indicate that a number of the coals from the Indian subcontinent also contain significant quantities of the alkali feldspars and of garnets, which must be included in this analysis.

- For the hard minerals in a coal to be involved in abrasion/erosion processes they must be liberated from the carbonaceous matrix, i.e. only excluded mineral occurrences should be included in the analysis.

- It has also been reported that the abrasion and erosion characteristics of the mineral particles depend on the particle size. Below a certain size, the abrasiveness and erosiveness of the particles are negligible.

- It has also been reported that the particle shape also has an impact on the abrasion and erosion characteristics of mineral particles. The angularity of mineral particles is not easy to define from CCSEM data. It was observed that the test coals contain both rounded and angular mineral particles, and the average aspect ratio values and asperities for both the quartz and pyrite occurrences in the test coals were very similar. It was decided therefore that the effect of particle shape on the abrasion and erosion characteristics would be fairly similar for all the coals, and, to avoid over-complication of the analysis, variations in this parameter would not be considered.

The starting point for correlations was to consider the mini-mill abrasion and pf erosion data as functions of quartz, pyrite, feldspar and garnet contents (volume percent) of the different coals, as determined by CCSEM. The quartz and pyrite contents can be estimated from the chemical composition of the coal, and can be measured quantitatively using CCSEM techniques.

The measured abrasion and erosion rates have been plotted against the total hard mineral contents of the test coals (volume percent) in Figures 8 and 9. As was found previously, although there are general trends, with the measured abrasion and erosion rates for the test coals increasing with increasing hard mineral content, the correlations were very poor.

The next step was to apply the other assumptions described above, i.e.

- To include only excluded mineral particles, and

- To include only those particles with diameters greater than 32 μm.

The correlations obtained using these assumptions were much improved. Taking the particle size cut at 32 μm did, however, present a problem in that only a relatively small number of particles lie in this range, and the data become statistically unreliable.

It was found that a better result was obtained when the particle size cut was taken at 25 μm, and the correlations obtained in this way are reproduced in Figures 10 and 11. It is clear that very good linear correlations between the measured abrasion and erosion rates of the coals and the volume percent of excluded hard minerals particles with diameters greater than 25 μm were derived. The $r^2$ values are 0.945 and 0.99, respectively.

The very good correlations indicate that the assumptions described above are technically sound, and that the abrasive and erosive properties of pulverised coals are determined by the quantities of larger, excluded hard mineral particles that they contain.

## 7. CONCLUSIONS

This report is concerned with the results of an investigation into the abrasion and erosion characteristics of a suite of coals, which have been specifically selected to represent the full range of ash contents and ash characteristics that are commonly encountered by the suppliers and operators of coal-fired boiler plants on a worldwide basis. These coals have been characterised in some detail both by conventional laboratory techniques, and by the use of Computer Controlled Scanning Electron Microscopy (CCSEM) techniques. The CCSEM is a relatively novel approach to coal and coal ash characterisation, which can be used to provide quantitative microstructural information that is not available by any other means.

The abrasion work was specifically concerned with the behaviour of coals in milling plant, and particularly in vertical spindle, ball and ring mills. The abrasion rate measurements were conducted using a small test mill, the Mini-mill Test Facility, which is operated by Mitsui Babcock in Renfrew. The use of this facility permitted the direct measurement of the weight losses from the mill grinding elements, when the coals were milled under standardised conditions.

The erosion work was performed using the Erosion Test Rig, also operated by Mitsui Babcock in Renfrew. There were two principal aspects to this work, viz:

- A study of the relative erosion rates associated with the suite of coals described above, under standardised test conditions, and

- A study of the relative erosion resistance of a range of target materials, including a number of specialist metallic and other coating materials.

One of the principal objectives of the work was to develop improved correlations between the measured abrasion and erosion behaviour of the coals and their ash characteristics, as determined using the CCSEM techniques. It has been found that both the abrasion and erosion characteristics of the coals can be attributed to the relatively small quantities of hard mineral particles present in the coals. More specifically, it was found that the measured abrasion and erosion wear rates associated with the test coals were controlled by the total quantity of these mineral species that are greater than 25 μm in diameter and that are liberated or excluded, i.e. which are not included within larger particles either of coal substance or of the clay minerals, which tend to by the most abundant constituents of the coals.

Very good linear correlations have been obtained between the measured abrasion and erosion rates for the test coals and the total quantities of the larger, hard, excluded mineral particles that the coals contain, expressed as a volume percentage. This type of quantitative information on the mineral characteristics of the coals can only be obtained by CCSEM techniques.

These findings represent a significant step forward in this subject area, in that they confirm in a compelling fashion that the erosion and abrasion behaviour of coals is controlled principally by the hard mineral particles, as has been suspected for some time. The results also provide the industry with a means of predicting the abrasion and erosion behaviour of unfamiliar coals. This is of direct value both to the suppliers of coal milling and combustion equipment, who have to provide guarantees of component life, and to the operators of coal-fired power plants in the development of coal purchasing strategies and maintenance schedules. It is anticipated that these results will be of direct benefit to the project partners, and principally to the industrial partners, Mitsui Babcock and PowerGen, who both have commercial interests in the abrasion and erosion behaviour of coals and in the impact of abrasive and erosive wear on the performance and integrity of coal processing plant.

## 8. SUGGESTIONS FOR FURTHER WORK

Overall, therefore, it is clear that the results described in this report are very encouraging. It should be noted, however, that further work to extend the range of coals on which these correlations are based, i.e. further coals should be subjected to the programme of Mini-mill and erosion rig testing, and to CCSEM analysis. This will involve the collection of small samples of coals of interest, perhaps 50 kg or so, the testing of these coals in the Mini-mill Test Facility and the production of pulverised coal samples for erosion rig testing and CCSEM analysis. An assessment of the abrasion and erosion characteristics of an unfamiliar coal could be performed in this way at relatively modest cost. It is possible that this approach to the erosion and abrasion assessment of coals could be provided as a service to third party customers on a consultancy basis.

It should also be noted that the measurement of both the abrasive and erosive wear rates was performed on relatively small-scale test equipment. Although this was done to provide a degree of control over the test conditions and to allow a wide range of coals to be tested at reasonable cost, there must always be some doubt as to whether the results of this type of work accurately reflect industrial-scale plant behaviour. This concern applies to the results of all small-scale testwork, but is particularly relevant in this subject area, because of the difficulties in obtaining meaningful and quantitative data on the abrasion and erosion rates of industrial plant components.

It is suggested that this would be a very interesting area of future work in this subject, now that there is a good appreciation of the basic science of coal abrasion and erosion, and the correlations between the coal characteristics and the results of rig tests are available. It is also suggested that the focus for future work in this subject area should be on the development of an improved understanding of plant behaviour and the collection of meaningful data on the abrasion and erosion rates in industrial scale coal processing equipment.

The work on the erosion behaviour of samples of pulverised coal ash, produced by combustion of two of the test coals in the Combustion Test Rig operated by PowerGen at Ratcliffe, indicated that the overall effect of the mineral transformations in the flame was to increase the erosiveness of the fly ash materials compared to that of the original mineral material. It was also noted that the erosive behaviour of the two fly ashes was fairly similar. These findings provide further evidence that the erosion of heat exchange tubes in the convective sections of the boiler is controlled largely by the ash particle concentration and by the local gas velocities, and that the differences between the ash characteristics are likely to represent a second order effect in most cases.

The work on the relative erosion resistance of a range of materials has indicated that the normal steels employed for boiler tubes and other components have very similar erosion wear rates when impacted with pulverised coal particles at controlled velocities. The harder ferrous metals, for instance the high chrome cast irons, can provide a 2-3 times reduction in the erosion rates and for this reason, these materials have been employed for the construction of the some of the internal components of pulverised coal burners, where erosion wear associated with concentrated streams of pulverised coal particles is a common problem.

The results of the erosion testwork with the specialised coatings indicated that reductions in erosion wear rates by up to a factor of ten were measured for the tungsten carbide and chromium carbide coatings. The employment of coatings of this type should be given serious consideration particularly for relatively small components, which are subject to severely erosive conditions, and where a compelling economic case for their use can be made.

## 9. REFERENCES

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# TABLES

|  | Rossington |  | Powder River Basin |  | Bailey |  | La Loma |  | Hunter Valley |  | Rietspruit |  | Oxcroft |  |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Proximate (wt %)** | dry | as rec'd | dry | as rec'd | dry | as rec'd | dry | as rec'd | dry | as rec'd | dry | as rec'd | dry | as rec'd |
| raw coal |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| moisture |  | 11.5 |  | 28.8 |  | 5.6 |  | 13.3 |  | 8.0 |  | 8.2 |  | 13.3 |
| volatiles | 36.1 | 32.0 | 42.2 | 30.0 | 35.9 | 33.9 | 38.1 | 33.0 | 31.4 | 28.9 | 27.8 | 25.5 | 31.1 | 27.0 |
| fixed carbon | 58.8 | 52.0 | 49.8 | 35.5 | 54.9 | 51.8 | 52.1 | 45.2 | 57.5 | 52.9 | 57.1 | 52.4 | 53.0 | 45.9 |
| ash | 5.1 | 4.5 | 8.0 | 5.7 | 9.2 | 8.7 | 9.8 | 8.5 | 11.1 | 10.2 | 15.1 | 13.9 | 15.9 | 13.8 |
| **Forms of sulphur** (wt % dry basis) |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| total | 1.12 |  | 0.42 |  | 1.30 |  | 0.79 |  | 0.49 |  | 0.75 |  | 1.92 |  |
| sulphate | 0.01 |  | <0.01 |  | 0.13 |  | 0.08 |  | 0.10 |  | 0.01 |  | 0.01 |  |
| pyritic | 0.42 |  | 0.07 |  | 0.50 |  | 0.29 |  | 0.06 |  | 0.36 |  | 1.25 |  |
| organic | 0.69 |  | 0.34 |  | 0.67 |  | 0.42 |  | 0.33 |  | 0.38 |  | 0.67 |  |
| **Ash analysis (wt%)** |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| $SiO_2$ | 39.7 |  | 39.7 |  | 52.1 |  | 66.9 |  | 81.2 |  | 46.1 |  | 48.0 |  |
| $Al_2O_3$ | 26.5 |  | 16.0 |  | 27.5 |  | 19.4 |  | 13.2 |  | 27.0 |  | 27.6 |  |
| $Fe_2O_3$ | 16.0 |  | 7.6 |  | 11.9 |  | 7.7 |  | 3.4 |  | 5.0 |  | 14.5 |  |
| $CaO$ | 5.3 |  | 16.6 |  | 2.1 |  | 1.54 |  | 0.36 |  | 9.0 |  | 3.3 |  |
| $MgO$ | 1.6 |  | 4.5 |  | 1.1 |  | 0.86 |  | 0.28 |  | 2.6 |  | 2.0 |  |
| $TiO_2$ | 1.2 |  | 1.3 |  | 1.5 |  | 0.78 |  | 0.56 |  | 1.36 |  | 0.80 |  |
| $Na_2O$ | 4.2 |  | 1.5 |  | 0.39 |  | 0.41 |  | 0.22 |  | 0.53 |  | 0.48 |  |
| $K_2O$ | 1.9 |  | 0.6 |  | 2.0 |  | 1.59 |  | 0.68 |  | 0.48 |  | 2.6 |  |
| $P_2O_5$ | 0.15 |  | 1.1 |  | 0.10 |  | 0.13 |  | 0.06 |  | 1.54 |  | 0.19 |  |
| $SO_3$ | 3.3 |  | 11.2 |  | 1.3 |  | 0.67 |  | 0.10 |  | 6.71 |  | 0.50 |  |
| **Calculated percentages** |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| pyrite in coal | 0.79 |  | 0.13 |  | 0.94 |  | 0.55 |  | 0.11 |  | 0.68 |  | 2.35 |  |
| quartz in ash | 0.0 |  | 15.7 |  | 10.9 |  | 37. |  | 61.4 |  | 5.6 |  | 606 |  |
| quartz in coal | 0.0 |  | 1.3 |  | 1.0 |  | 3.7 |  | 6.8 |  | 0.8 |  | 1.0 |  |
| **Hardgrove Index** | 52 |  | 57 |  | 54 |  | 45 |  | 51 |  | 55 |  | 73 |  |
| **Abrasion Index** mg/kg | 12 |  | 22 |  | 5 |  | 55, 41 |  | 18, 21 |  | 15 |  | 33 |  |

**Table 1 (a): Basic characterisation of the test coals (1 of 2)**

<table>
<tr><th></th><th colspan="2">Harworth</th><th colspan="2">Bakreswar</th><th colspan="2">Rihand</th><th colspan="2">Koradi</th><th colspan="2">Talcher</th><th colspan="2">Satpura</th></tr>
<tr><td><b>Proximate (wt %)</b></td><td>dry</td><td>as rec’d</td><td>dry</td><td>as rec’d</td><td>dry</td><td>as rec’d</td><td>dry</td><td>as rec’d</td><td>dry</td><td>as rec’d</td><td>dry</td><td>as rec’d</td></tr>
<tr><td>raw coal</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>moisture</td><td></td><td>10.0</td><td></td><td>8.7</td><td></td><td>14.4</td><td></td><td>5.5</td><td></td><td>11.9</td><td></td><td>2.7</td></tr>
<tr><td>volatiles</td><td>29.4</td><td>26.5</td><td>27.4</td><td>25.0</td><td>27.5</td><td>23.6</td><td>24.9</td><td>23.5</td><td>25.6</td><td>22.6</td><td>19.7</td><td>19.2</td></tr>
<tr><td>fixed carbon</td><td>48.4</td><td>43.5</td><td>38.0</td><td>34.7</td><td>30.5</td><td>26.1</td><td>31.3</td><td>29.6</td><td>29.1</td><td>25.6</td><td>31.2</td><td>30.3</td></tr>
<tr><td>ash</td><td>22.2</td><td>20.0</td><td>34.6</td><td>31.6</td><td>42.0</td><td>36.0</td><td>43.8</td><td>41.4</td><td>45.3</td><td>39.9</td><td>49.1</td><td>47.8</td></tr>
<tr><td><b>Forms of sulphur</b><br>(wt % dry basis)</td><td colspan="2"></td><td colspan="2"></td><td colspan="2"></td><td colspan="2"></td><td colspan="2"></td><td colspan="2"></td></tr>
<tr><td>total</td><td colspan="2">2.35</td><td colspan="2">0.40</td><td colspan="2">0.48</td><td colspan="2">0.54</td><td colspan="2">0.41</td><td colspan="2">0.47</td></tr>
<tr><td>sulphate</td><td colspan="2">0.12</td><td colspan="2">0.02</td><td colspan="2">0.02</td><td colspan="2">0.02</td><td colspan="2"><0.01</td><td colspan="2">0.01</td></tr>
<tr><td>pyritic</td><td colspan="2">1.37</td><td colspan="2">0.18</td><td colspan="2">0.36</td><td colspan="2">0.31</td><td colspan="2">0.10</td><td colspan="2">0.28</td></tr>
<tr><td>organic</td><td colspan="2">0.86</td><td colspan="2">0.20</td><td colspan="2">0.11</td><td colspan="2">0.21</td><td colspan="2">0.30</td><td colspan="2">0.18</td></tr>
<tr><td><b>Ash analysis (wt %)</b></td><td colspan="2"></td><td colspan="2"></td><td colspan="2"></td><td colspan="2"></td><td colspan="2"></td><td colspan="2"></td></tr>
<tr><td>$SiO_2$</td><td colspan="2">50.8</td><td colspan="2">63.2</td><td colspan="2">62.0</td><td colspan="2">65.1</td><td colspan="2">66.4</td><td colspan="2">67.2</td></tr>
<tr><td>$Al_2O_3$</td><td colspan="2">28.1</td><td colspan="2">22.8</td><td colspan="2">26.2</td><td colspan="2">26.6</td><td colspan="2">24.0</td><td colspan="2">23.9</td></tr>
<tr><td>$Fe_2O_3$</td><td colspan="2">12.1</td><td colspan="2">6.5</td><td colspan="2">5.8</td><td colspan="2">4.6</td><td colspan="2">3.0</td><td colspan="2">4.4</td></tr>
<tr><td>CaO</td><td colspan="2">1.23</td><td colspan="2">1.6</td><td colspan="2">0.58</td><td colspan="2">0.59</td><td colspan="2">1.6</td><td colspan="2">0.68</td></tr>
<tr><td>MgO</td><td colspan="2">1.24</td><td colspan="2">1.3</td><td colspan="2">0.40</td><td colspan="2">0.45</td><td colspan="2">0.7</td><td colspan="2">1.04</td></tr>
<tr><td>$TiO_2$</td><td colspan="2">0.91</td><td colspan="2">1.3</td><td colspan="2">1.61</td><td colspan="2">1.76</td><td colspan="2">1.3</td><td colspan="2">1.49</td></tr>
<tr><td>$Na_2O$</td><td colspan="2">1.11</td><td colspan="2">0.32</td><td colspan="2">0.16</td><td colspan="2">0.11</td><td colspan="2">0.1</td><td colspan="2">0.36</td></tr>
<tr><td>$K_2O$</td><td colspan="2">3.5</td><td colspan="2">2.0</td><td colspan="2">0.62</td><td colspan="2">0.65</td><td colspan="2">1.7</td><td colspan="2">0.65</td></tr>
<tr><td>$P_2O_5$</td><td colspan="2">0.32</td><td colspan="2">1.0</td><td colspan="2">0.05</td><td colspan="2">0.22</td><td colspan="2">1.0</td><td colspan="2">0.07</td></tr>
<tr><td>$SO_3$</td><td colspan="2">0.76</td><td colspan="2">0.1</td><td colspan="2">2.68</td><td colspan="2">0.07</td><td colspan="2">0.1</td><td colspan="2">0.14</td></tr>
<tr><td><b>Calculated percentages</b></td><td colspan="2"></td><td colspan="2"></td><td colspan="2"></td><td colspan="2"></td><td colspan="2"></td><td colspan="2"></td></tr>
<tr><td>pyrite in coal</td><td colspan="2">2.58</td><td colspan="2">0.34</td><td colspan="2">0.04</td><td colspan="2">0.58</td><td colspan="2">0.19</td><td colspan="2">0.02</td></tr>
<tr><td>quartz in ash</td><td colspan="2">8.6</td><td colspan="2">29.0</td><td colspan="2">22.7</td><td colspan="2">25.2</td><td colspan="2">30.4</td><td colspan="2">31.4</td></tr>
<tr><td>quartz in coal</td><td colspan="2">1.9</td><td colspan="2">10.0</td><td colspan="2">9.5</td><td colspan="2">11.0</td><td colspan="2">13.8</td><td colspan="2">15.4</td></tr>
<tr><td><b>Hardgrove Index</b></td><td colspan="2">79</td><td colspan="2">58</td><td colspan="2">105</td><td colspan="2">55</td><td colspan="2">59</td><td colspan="2">53</td></tr>
<tr><td><b>Abrasion Index</b> mg/kg</td><td colspan="2">19</td><td colspan="2">52</td><td colspan="2">41</td><td colspan="2">59</td><td colspan="2">43</td><td colspan="2">102</td></tr>
</table>

**Table 1 (b)**: **Basic characterisation of the test coals (2 of 2)**

| | Rossing-ton | Powder River Basin | Bailey | La Loma | Hunter Valley | Riets-pruit | Harworth | Bakre-swar | Talcher | Satpura |
|---|---|---|---|---|---|---|---|---|---|---|
| **Mini mill feed rate (kg $h^{-1}$)** | 5.20 | 5.03 | 5.33 | 4.98 | 4.93 | 5.37 | 5.15 | 5.02 | 5.22 | 5.17 |
| **Feed specific surface area ($m^2$ $m^{-3}$)** | 27,195 | 23,129 | 43,571 | 39,060 | 31,782 | 58,149 | 59,029 | 62,300 | 46689 | 95,333 |
| **Product specific surface area ($m^2$ $m^{-3}$)** | 195,920 | 198,599 | 246,266 | 204,383 | 243,578 | 283,7846 | 334,276 | 261,131 | 319571 | 370,733 |
| **New surface area ($m^2$ $m^{-3}$)** | 168,725 | 175,470 | 202,698 | 165,623 | 211,796 | 225635 | 275,247 | 198,831 | 272882 | 275,400 |
| **Average net power consumption (W)** | 29 | 28 | 32.5 | 30 | 28 | 28 | 28 | 36 | 33.5 | 31 |
| **Energy consumption per unit new surface area (J $m^{-2}$)** | 158 | 128 | 147 | 180 | 132 | 118 | 110 | 177 | 125 | 139 |
| **Product fineness** | | | | | | | | | | |
| **% <75 µm** | 58 | 59 | 53 | 52 | 55 | 59 | 66 | 54 | 60 | 67 |
| **Topsize (µm)** | 300 | 300 | 300 | 300 | 300 | 300 | 300 | 300 | 300 | 300 |
| **Weight in rejects trap (g)** | 224 | 266 | 287 | 193 | 210 | 223 | 238 | 185 | 348 | 260 |
| **Weight loss (mg $kg^{-1}$ of coal)** | | | | | | | | | | |
| **Top ring** | 2.7 | 5.4 | 2.3 | 3.9 | 4.2 | 1.2 | 2.2 | 15.2 | 5.4 | 18.8 |
| **Bottom ring** | 2.6 | 2.8 | 1.9 | 4.1 | 3.2 | 0.5 | 1.6 | 12.8 | 3.4 | 13.5 |
| **Balls** | 6.0 | 13.6 | 4.0 | 12.2 | 16.6 | 9.3 | 10.7 | 45.8 | 22.6 | 59.6 |
| **Total** | 11.3 | 21.6 | 8.2 | 20.2 | 24.0 | 11.1 | 14.5 | 73.8 | 31.4 | 91.9 |

**Table 2**: **A summary of the results of the Mini-Mill Tests**

| **Mineral name** | Chemical formula | Hardness (Moh's scale) |
|---|---|---|
| **Zircon** | $ZrSiO_4$ | 7.5 |
| **Quartz** | $SiO_2$ | 7.0 |
| **Garnet** | $(Mg,Fe_2)Al_2Si_3O_{12}$ | 6.0-7.5 |
| **Feldspar** | $(K,Na)AlSi_3O_8$ | 6.0-6.5 |
| **Pyrite/Marcasite** | $FeS_2$ | 6.0-6.5 |
| **Rutile** | $TiO_2$ | 6.0-6.5 |
| **Ilmenite** | $FeTiO_3$ | 5.0-6.0 |
| **Mild steel** | **-** | **5.0-6.0** |
| **Apatite** | $Ca_5(PO_4)_3(OH)$ | 5.0 |
| **Siderite** | $FeCO_3$ | 4.0-4.5 |
| **Dolomite** | $Ca,Mg(CO_3)_2$ | 3.5-4.0 |
| **Ankerite** | $Ca(Mg,Fe)(CO_3)_2$ | 3.5-4.0 |
| **Anhydrite** | $CaSO_4$ | 3.5 |
| **Calcite** | $CaCO_3$ | 3.0 |
| **Muscovite** | $KAl_3Si_3O_{10}(OH)_4$ | 2.5-3.0 |
| **Kaolinite** | $Al_2Si_2O_5(OH)_4$ | 2.0-2.5 |
| **Gypsum** | $CaSO_4.2H_2O$ | 2.0 |

**Table 3: A list of the more common mineral species found in coals with their Moh's Hardness values, compared to that of mild steel**

| Pulverised Coal | Ash Content (%, as used) | Velocity Exponent | Erosion Rate at 40 m $s^{-1}$ (mg $kg^{-1}$ of pulverised coal) |
|---|---|---|---|
| **Rossington** | 6.4 | 3.01 | 0.56 |
| **PRB** | 6.8 | 2.01 | 0.67 |
| **Bailey** | 8.5 | 2.00 | 0.47 |
| **La Loma** | 7.8 | 3.15 | 0.83 |
| **Hunter Valley** | 10.8 | 2.78 | 0.91 |
| **Rietspruit** | 14.9 | 2.01 | 1.01 |
| **Harworth** | 19.6 | 2.54 | 0.69 |
| **Bakreswar** | 28.7 | 1.69 | 2.87 |
| **Talcher** | 44.1 | 2.37 | 1.15 |
| **Satpura** | 44.4 | 2.44 | 5.26 |

**Table 4: A summary of the results of the standard erosion tests on the pulverised coal samples (impact angle 45º)**

| Parameter | Hunter Valley | Bailey |
|---|---|---|
| **Moisture content of pulverised coal, (%)** | 3.9 | 2.9 |
| **Ash content of pulverised coal, (%, dry basis)** | 11.2 | 8.8 |
| **Erosion rate for pulverised coal, (mg $kg^{-1}$ of coal)** | 0.91 | 0.47 |
| **Erosion rate for pulverised coal, (mg $kg^{-1}$ of ash)** | 8.49 | 5.44 |
| **Erosion rate for pulverised coal ash, (mg $kg^{-1}$)** | 9.65 | 7.60 |

**Table 5: Erosion rate data for the Hunter Valley and Bailey pulverised coals and pulverised coal ashes**

| **Material**<br>(manufacturer's ref.) | **Surface condition** | **Mass wear rate (mg/kg)** | **Volume wear rate ($mm^3/kg^{-1}$)** |
|---|---|---|---|
| **Carbon Steel** | as ground | 2.41 | 0.31 |
| **25%Cr cast iron** | as ground | 0.89 | 0.12 |
| **Nickel/Chromium 80/20**<br>(ME-18) | as received<br>polished | 3.24<br>2.95 | 0.41<br>0.37 |
| **Stellite 6** | as received<br>polished | 2.10<br>2.14 | 0.23<br>0.24 |
| **80:20 Cr Carbide/NiCr**<br>(CA05) | as received<br>polished | 0.38<br>0.26 | 0.038<br>0.026 |
| **W Carbide/12% Co**<br>(CA-09) | as received<br>polished | 0.34<br>0.36 | 0.028<br>0.030 |

**Table 6: The erosion wear rates of the test materials**

| Coal | Main quartz in coal (vol.%) | Amount "Contained" | Wt.% average particle size (μm) | Quartz > 16 μm | Quartz > 32 μm | Wt.% average aspect ratio | Further quartz associated with clays (vol.%) |
|---|---|---|---|---|---|---|---|
| **Rossington** | 0.06 | 0 % | 2-4 | 0 % | 0 % | 1.8 | 0.05 |
| **Powder River Basin** | 0.89 | 11 % | 8-16 | 36 % | 17 % | 1.7 | 0.25 |
| **Talcher** | 5.98 | 4 % | 4-8 | 17 % | 0 % | 1.8 | 4.07 |
| **Bakreswar** | 2.44 | 3 % | 4-8 | 23 % | 7 % | 1.9 | 1.19 |
| **Hunter Valley** | 3.09 | 19 % | 4-8 | 14 % | 7 % | 1.9 | 0.56 |
| **Bailey** | 0.39 | 22 % | 4-8 | 0 % | 0 % | 2.2 | 0.11 |
| **La Loma** | 1.40 | 1 % | 16-32 | 52 % | 32 % | 1.6 | 0.44 |
| **Rietspruit** | 1.05 | 18 % | 4-8 | 22 % | 11 % | 2.0 | 0.28 |
| **Oxcroft** | 0.29 | 1 % | 4-8 | 10 % | 0 % | 1.9 | 0.12 |
| **Satpura** | 3.92 | 3 % | 16-32 | 55 % | 27 % | 1.9 | 1.99 |
| **Harworth** | 0.30 | 7 % | 2-4 | 22 % | 19 % | 1.8 | 0.22 |
| **Mao Khe** | 2.37 | 0 % | 4-8 | 14 % | 0 % | 1.9 | 1.78 |

**Table 7: The characteristics of the quartz associated with the pulverised coals**

| Coal | Main pyrite in coal (vol.%) | Amount "contained" | Wt.% average particle size (μm) | Pyrite > 16 μm | Pyrite > 32 μm | Wt.% average aspect ratio | Further pyrite associated with clays (vol.%) |
|---|---|---|---|---|---|---|---|
| **Rossington** | 0.29 | 3 % | 8-16 | 42 % | 35 % | 1.4 | 0.01 |
| **Powder River Basin** | 0.06 | 0 % | 8-16 | 48 % | 0 % | 2.0 | 0.08 |
| **Talcher** | 0.06 | 0 % | 4-8 | 31 % | 0 % | 1.8 | - |
| **Bakreswar** | 0.04 | 0 % | 16-32 | 84 % | 0 % | 1.7 | - |
| **Hunter Valley** | 0.01 | - | - | - | - | - | - |
| **Bailey** | 0.26 | 4 % | 8-16 | 31 % | 0 % | 1.7 | 0.04 |
| **La Loma** | 0.11 | 20 % | 4-8 | 18 % | 0 % | 2.0 | 0.06 |
| **Rietspruit** | 0.11 | 8 % | 8-16 | 43 % | 0 % | 1.9 | 0.04 |
| **Oxcroft** | 0.51 | 8 % | 4-8 | 15 % | 0 % | 1.5 | 0.14 |
| **Satpura** | - | - | - | - | - | - | 0.05 |
| **Harworth** | 0.39 | 13 % | 8-16 | 22 % | 0 % | 1.8 | 0.13 |
| **Mao Khe** | 0.04 | - |  | - | - | - | - |

**Table 8**: **Characteristics of the pyrite associated with the different pulverised coals**

| Coal | Main Alkspar in coal (vol.%) | Amount “contai-ned” | Wt.% average particle size (μm) | Alkspar > 16 μm | Alkspar > 32 μm | Wt.% average aspect ratio |
|---|---|---|---|---|---|---|
| **Talcher** | 0.87 | 0 % | 8-16 | 42 % | 0 % | 1.7 |
| **Bakreswar** | 1.91 | 0 % | 16-32 | 68 % | 43 % | 1.9 |
| **Satpura** | 1.59 | 0 % | 16-32 | 63 % | 55 % | 1.7 |

**Table 9: The characteristics of the alkali-feldspar associated with the Indian pulverised coals**

| Coal | Main Garnet in coal (vol.%) | Amount “contained” | Wt.% average particle size (μm) | Garnet > 16 μm | Garnet > 32 μm | Wt.% average aspect ratio |
|---|---|---|---|---|---|---|
| **Talcher** | 0 | - | - | - | - | - |
| **Bakreswar** | 0.14 | 0 % | 4-8 | 13 % | 0 % | 2.8 |
| **Satpura** | 0.32 | 11 % | 4-8 | 7 % | 0 % | 2.8 |

**Table 10: The characteristics of the garnet associated with the Indian pulverised coals**

# FIGURES

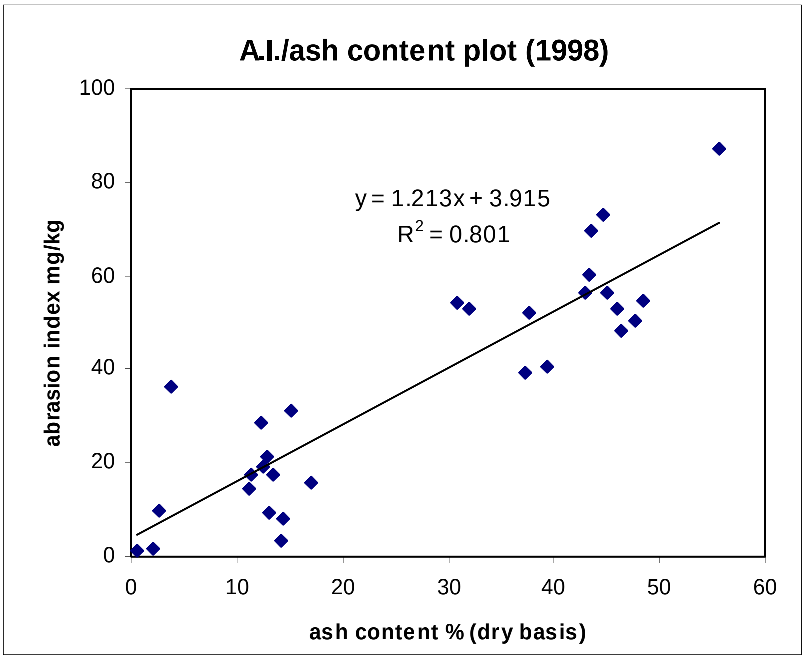

**Figure 1:** The Abrasion Index plotted against the ash content of coals contained in the Mitsui Babcock database

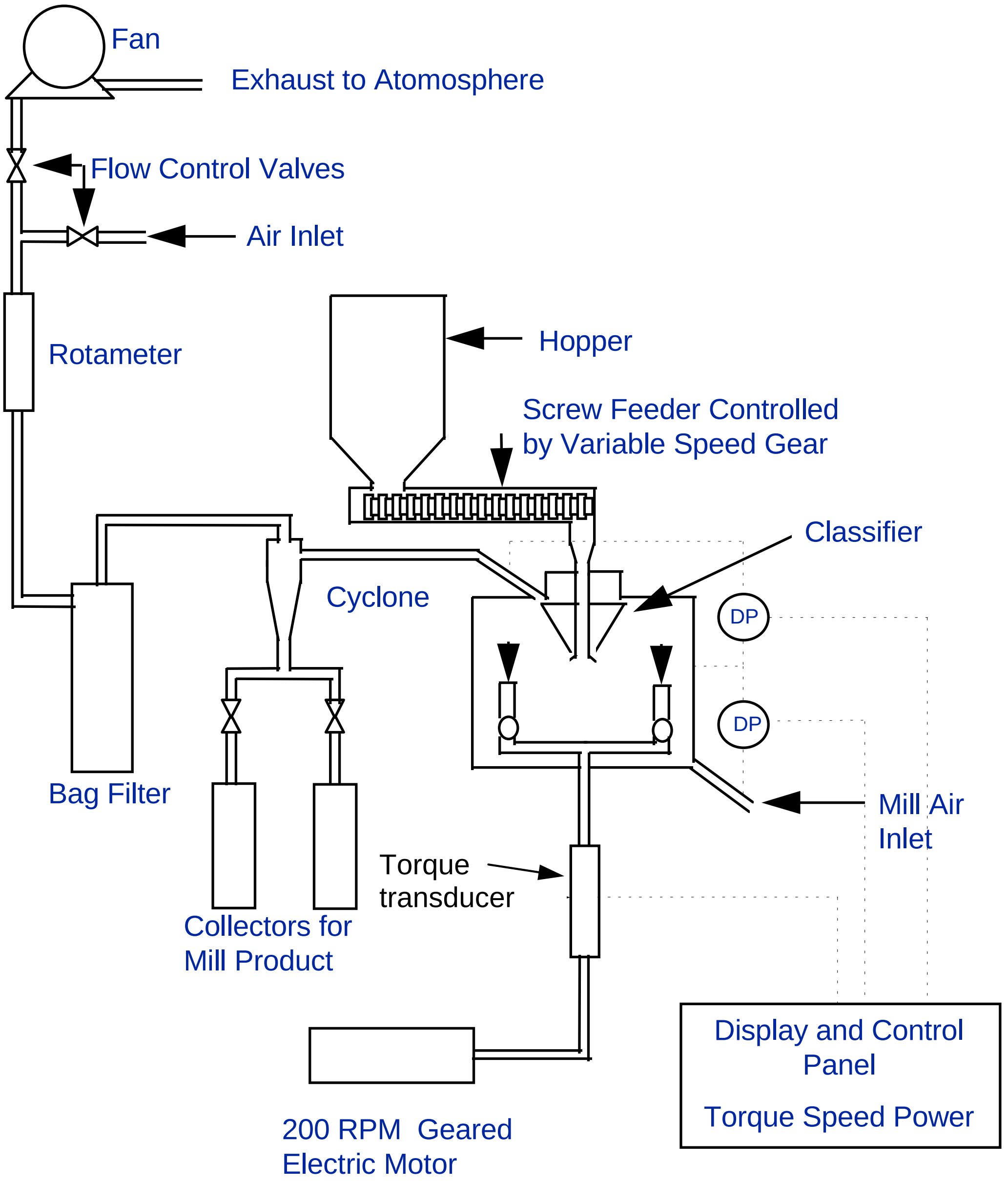

**Figure 2:** **A schematic diagram of mini-mill and associated equipment**

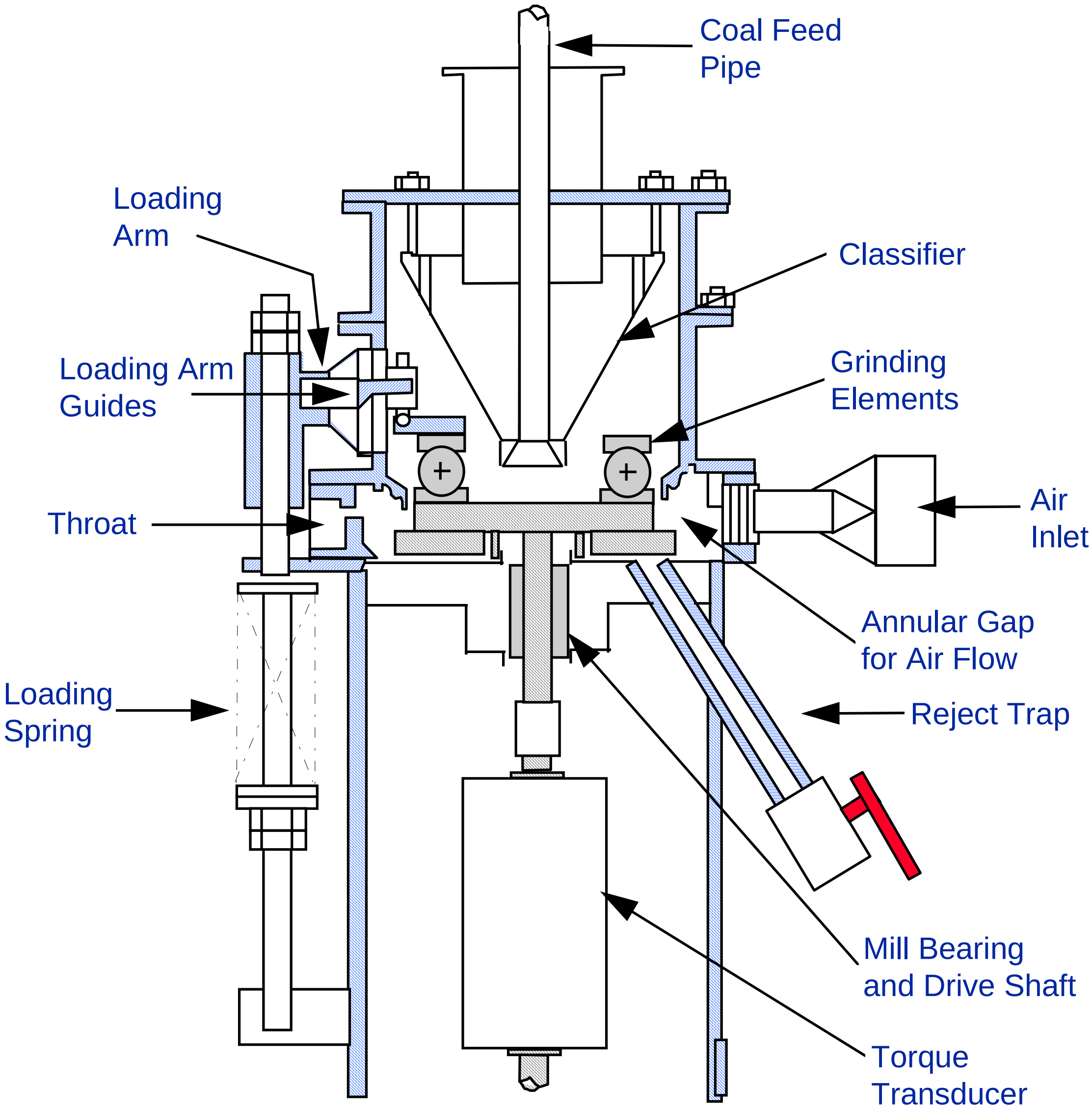

**Figure 3:** **A schematic diagram of the Mini-mill assembly**

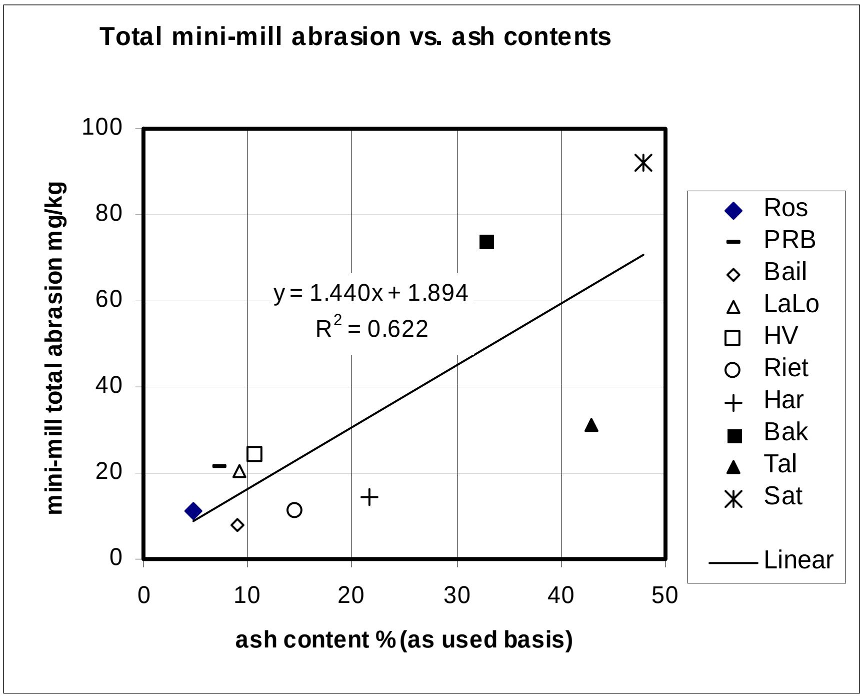

**Figure 4.** **The relationship between the mini-mill abrasion rate and the coal ash content**

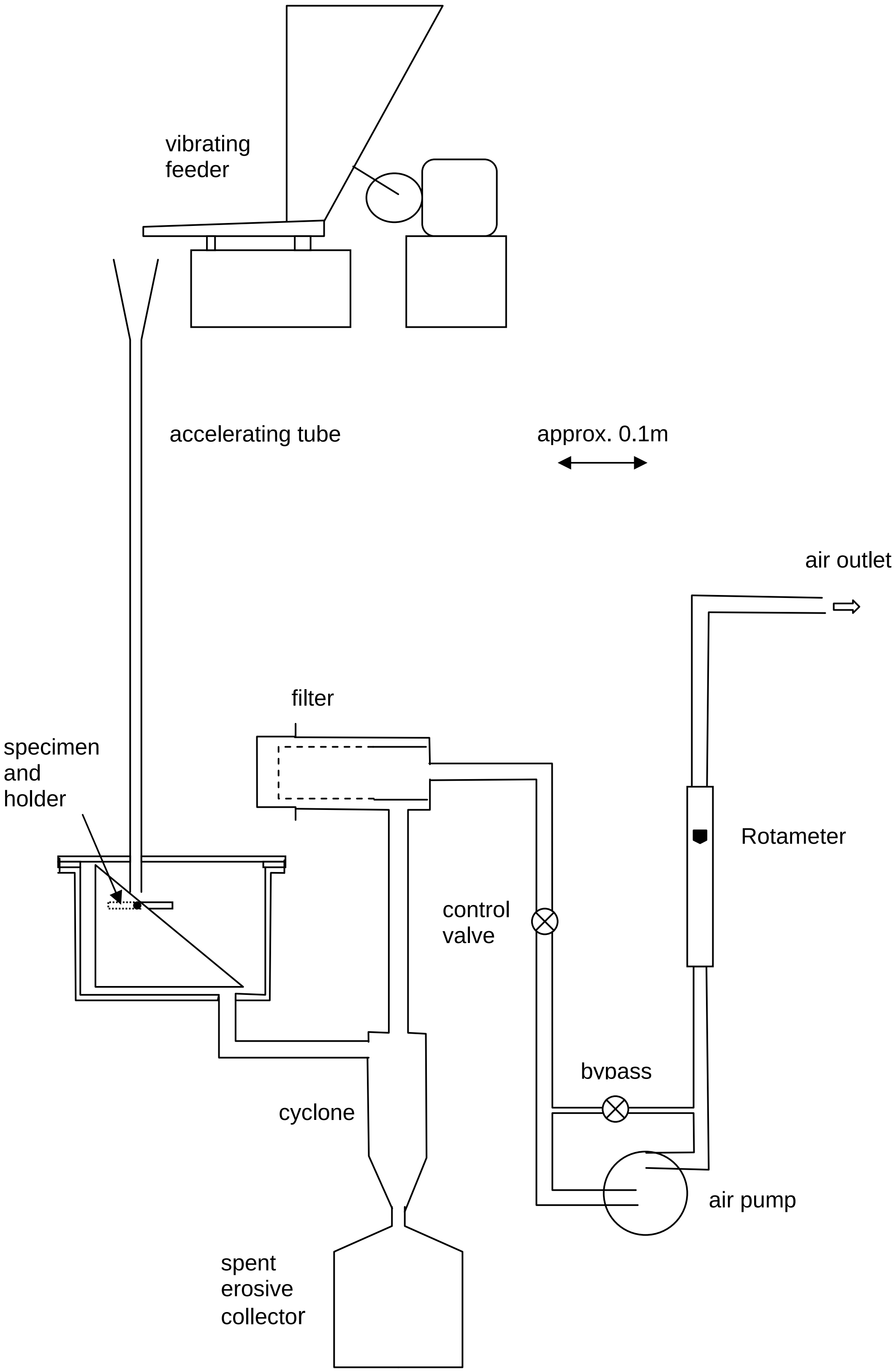

**Figure 5:** **A schematic diagram of erosion test rig**

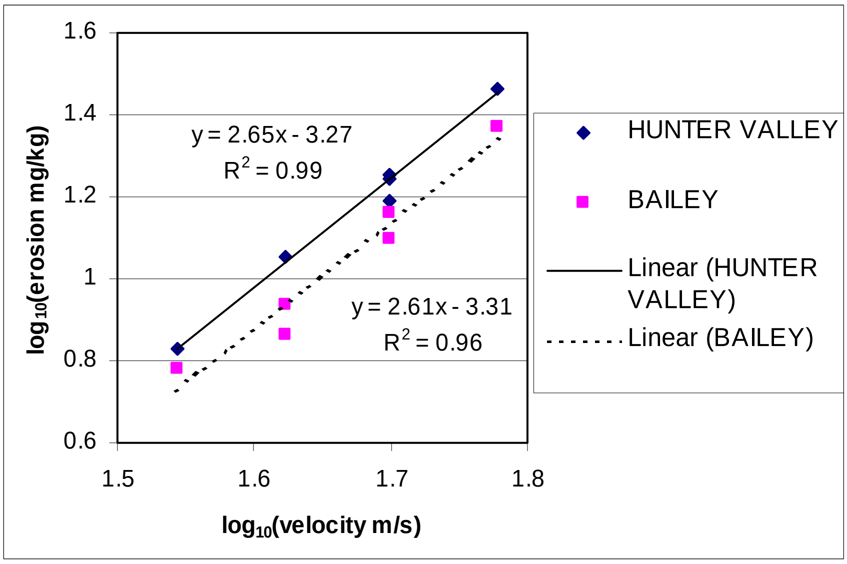

**Figure 6:** **The erosiveness of Bailey and Hunter Valley pulverised fuel ashes**

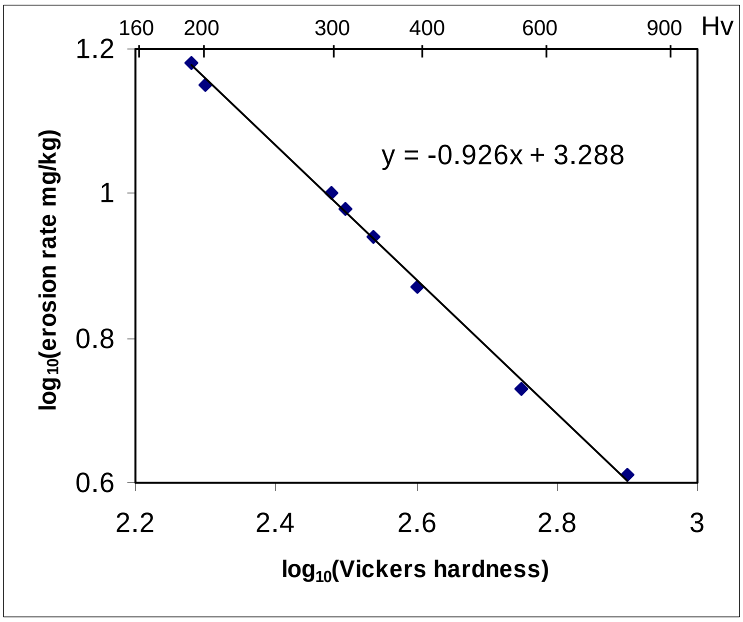

**Figure 7**: **The erosion rates of steels of different hardnesses by 125 - 250 µm quartz at 27.5 ms$^{-1}$ and 45º impact angle (from Raask 1988)**

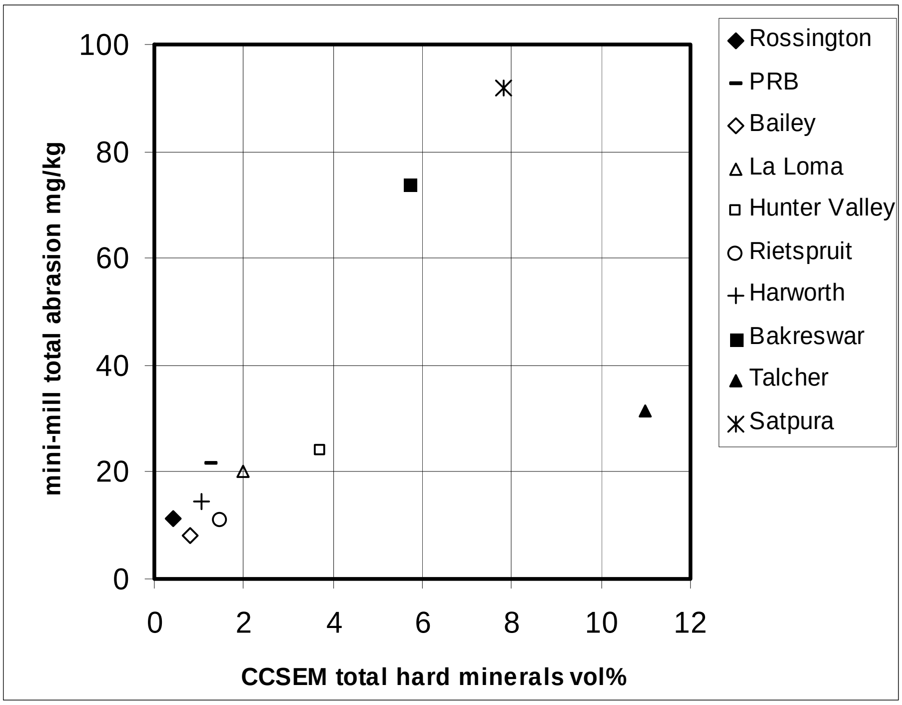

**Figure 8:** The total mini-mill abrasion rate plotted against the total hard minerals content (CCSEM) for the test coals.

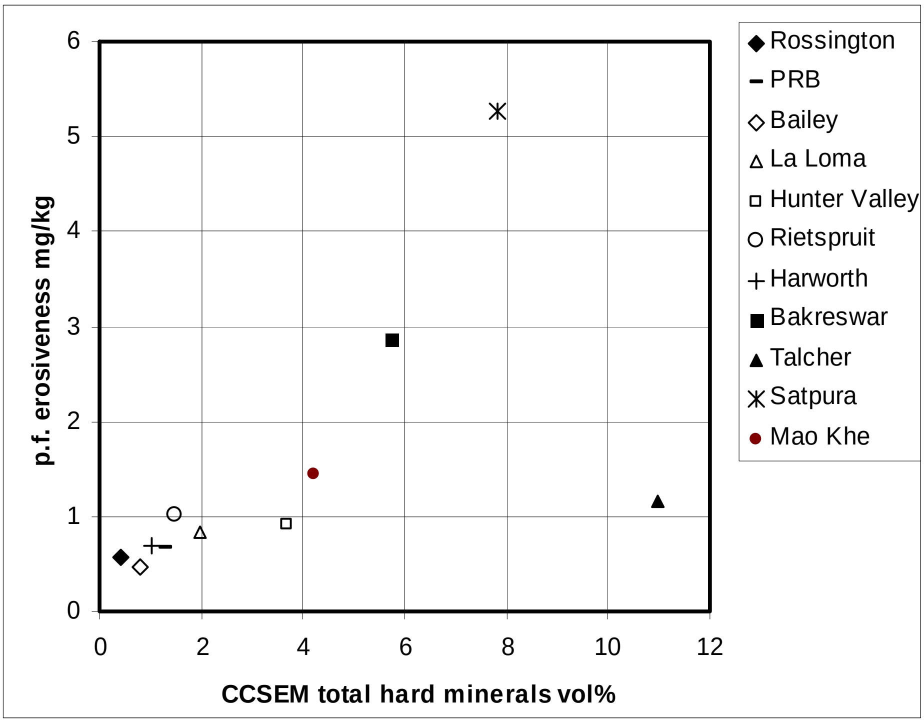

**Figure 9:** The erosion rate plotted against the total hard minerals content (CCSEM) for the pulverised test coals

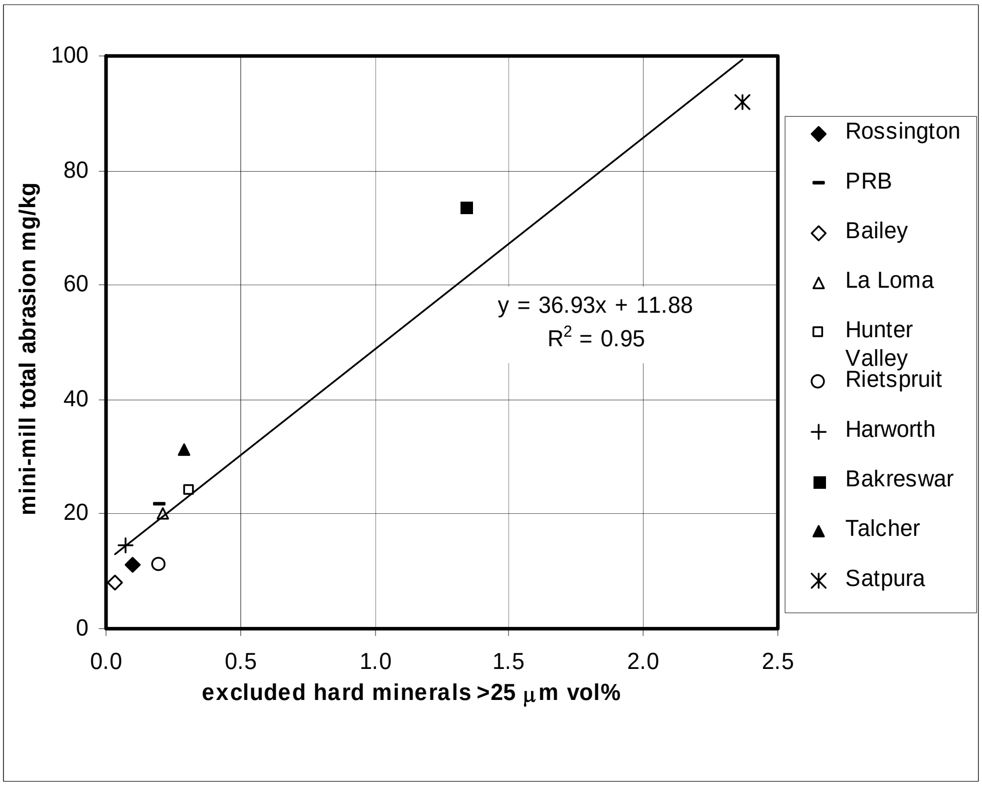

**Figure 10**: The Mini-mill abrasion rates plotted against the content of excluded hard minerals larger that 25 μm

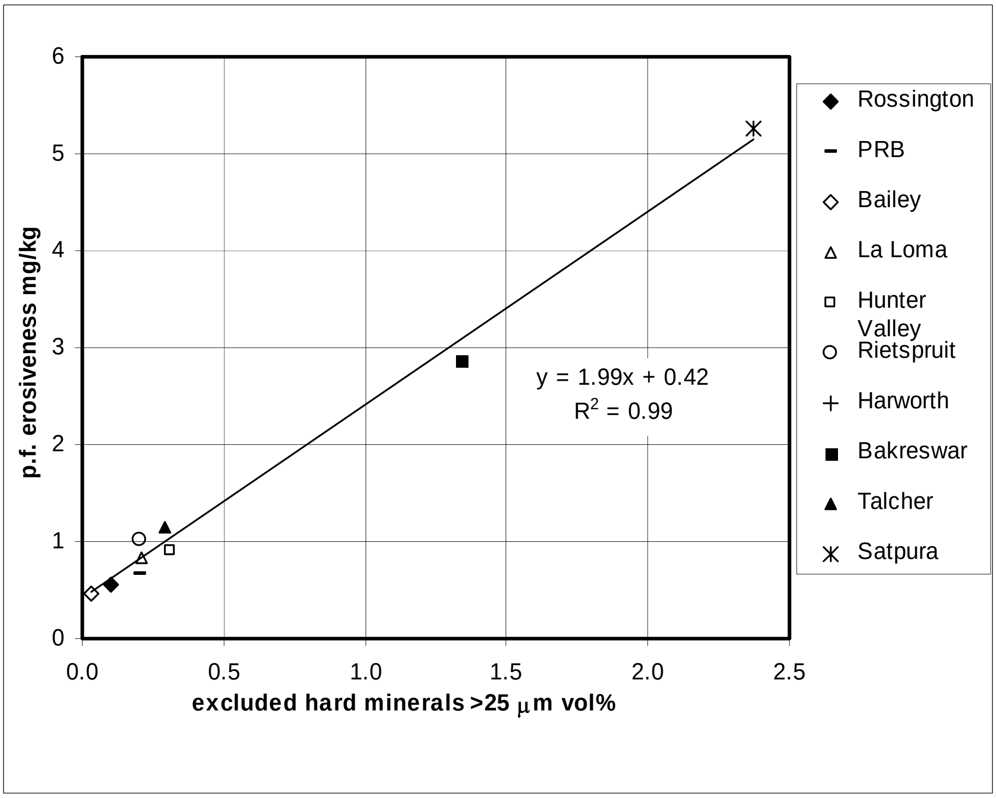

**Figure 11**: The erosion rate of the pulverised coals plotted against the content of excluded hard minerals larger that 25 μm