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CHEMOMECHANICAL PHENOMENA IN THE GRINDING OF COAL

Final Report, February 1, 1976—May 31, 1977

By
N. H. Macmillan

August 1977

Work Performed Under Contract No. EY-76-S-02-2871

Materials Research Laboratory
Pennsylvania State University
University Park, Pennsylvania

MASTER

U. S. DEPARTMENT OF ENERGY

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for Period February 1, 1976-May 31, 1977

N.H. Macmillan

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The Pennsylvania State University
University Park, Pennsylvania 16802

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Abstract

Vickers microhardness, drilling rate, grinding rate and zeta-potential measurements have been made on coals of various rank in both aqueous and organic environments in order to determine whether: (a) chemomechanical (Rebinder) effects exist in coal; and (b) any such effects as do exist can be used to improve the comminution of coal. The results reveal the mechanical behavior of coal to be remarkably environment-insensitive as compared to inorganic non-metals. As a result, it is concluded that chemomechanical phenomena offer little prospect of reducing the cost of comminuting coal.

TABLE OF CONTENTS

Abstract	iii
I. INTRODUCTION	1
II. EXPERIMENTAL: Materials and Methods	1
A. Coals: Selection and Examination	1
B. Environments	4
C. Microhardness Measurement	5
D. Drilling Rate Measurement	12
E. Grinding Rate Measurements	17
(i) Overview	17
(ii) Apparatus	22
(iii) Conventional HGI Determinations	22
(iv) HGI Determinations in Liquid Environments	23
(v) B & S Values: Theoretical Considerations	23
(vi) Determination of B Values	27
(vii) Determination of S Values	27
F. Zeta Potential Measurement	28
III. RESULTS	35
A. Coal Petrography	35
B. Microhardness	41
C. Drilling Rates	47
D. Grinding Rates	55
(i) HGI Determinations	55
(ii) B Values	64
(iii) S Values	69
E. Zeta Potentials	69
IV. DISCUSSION AND CONCLUSIONS	76
V. REFERENCES	81
VI. REPORTS AND PUBLICATIONS	82
VII. ACKNOWLEDGEMENTS	82

Appendix I Characterization Data for the 5 Principal Coals Employed

Appendix II Characterization Data for Illinois No. 6 Coal

I. INTRODUCTION

The purpose of this project was to explore the feasibility of using chemical grinding aids to reduce the cost of grinding coal. Specifically, it was desired to answer two questions: first, whether chemomechanical effects (i.e., chemisorption-induced variations in near-surface flow and flow-dependent fracture behavior) analogous to those occurring in inorganic non-metals⁽¹⁻⁵⁾ occur also in coal; and second, if they do, whether such variations can be parlayed into useful improvements in the efficiency of grinding coal. To these twin ends, correlations have been sought between the zeta potentials, the hardnesses, and the drilling and grinding characteristics of several coals of different rank in both aqueous and organic environments. It should be noted that, in keeping with the philosophy outlined in the original proposal, the aim of this work was exploratory rather than definitive--i.e., to search for and document such phenomena (and correlations between them) as might occur rather than to seek detailed mechanistic understanding. In the event, little influence of environment on the mechanical properties of coal has been observed, with the result that any search for mechanism becomes irrelevant.

II. EXPERIMENTAL: MATERIALS AND METHODS

A. Coals: Selection and Examination

By virtue of its chemical composition, coal has some of the characteristics of a polymeric material. Yet geologically it is a sedimentary rock having a distinct bedding plane and containing a mixture of petrographic constituents. Coal thus consists of layers of material laid down parallel to the bedding plane. And, as a result, it presents a banded appearance when seen in sections cut perpendicular to this plane. Even to the naked eye, coarse bands known as lithotypes* are frequently visible. These lithotypes, which typically are millimeters in thickness, are identifiable primarily by their color and their luster. However, optical microscopic examination reveals that these lithotypes are themselves composed of finer bands (typically tens or hundreds of microns thick) known, for obvious reasons, as microlithotypes*. And optical studies of thin sections of coal in transmitted light and of "pellets" (finely ground coal dispersed in a transparent resin matrix) in reflected light reveal that these microlithotypes are, in their turn, composed of characteristic combinations of so-called macerals*. Individual macerals--each of which derives from some particular vegetable origin--are thus somewhat analogous to the minerals in rocks. But, unlike minerals, macerals typically are non-uniform in both their chemical composition and their physical properties, and they are non-crystalline in structure.

Furthermore, coal frequently is not only extensively faulted, so that it contains a well developed macro-crack network, but it usually also possesses a substantial volume of internal microporosity. And, within this porous and faulted structure is usually incorporated significant quantities of more or less loosely bound water, much of which evaporates readily, producing extensive shrinkage and concomitant development of the fault system as it does so. Add to this the fact that coal normally also includes a variety of minerals dispersed throughout its volume in the form of particles of various shapes and sizes, and it can readily be appreciated that it is a complex and heterogeneous material of great

*Individual lithotype, microlithotype, and maceral names bear the suffixes "ain," "ite," and "inite," respectively.

variability. It is obviously therefore not the ideal solid for experimental study, if only because the great variability means that every measurement made on it must be repeated many times if statistically significant results are to be obtained.

However, it is well known that the mechanical properties of coal change in a more or less consistent manner with rank, although extraneous factors can obscure this basic pattern in particular instances. Hence, five coals of widely differing rank were employed in the majority of this work. These are listed in Table I in order of increasing rank, together with the Pennsylvania State University (PSU) identification numbers assigned them by the PSU Coal Research Station. The existence of these numbers--which signify that the key characteristics of these coals have been determined and are recorded in the computerized information retrieval system operated by that station--is another reason for their selection. Further considerations were that reproducible samples of each of these coals were readily available either on campus or at the mine in the form of lumps of adequate size, and that all five were of considerable industrial importance. Copies of the PSU Coal Research Station data sheets relevant to each are included as Appendix I of this report.

To examine the microstructures of and the pre-existing fracture patterns in these chosen coals, a polished (megascopic) section of each was prepared perpendicular to its bedding plane. These sections were then examined at normal incidence in dark field by reflection using white light and immersion oil of refractive index 1.520 to improve the contrast. The steps involved in the preparation of these specimens are listed below, and the micrographs obtained from them appear in Section III A.

- (i) Cut rectangular 2.5 x 2.5 cm slabs, oriented perpendicular to the bedding plane and about 1.5 thick, from large lumps of coal using a water-cooled diamond saw*.
- (ii) Mount the slab in Koldmount** self-curing resin so that the bedding plane is perpendicular to the resin surface.
- (iii) Wet grind on 240, 320, 400 and 600 grit SiC papers in turn.
- (iv) Final polish on Buehler† Texmet cloth using first a slurry of 0.3 μm Al_2O_3 abrasive in water and then a similar slurry of 0.05 μm Al_2O_3 powder, rinsing thoroughly in running water after both polishes.

Table I. The Coals Employed in This Work

Type (Rank)	Origin					PSU Identification Number
	Seam	Mine	City or Town	County	State	
Lignite	Coteau	Glen Harold	Stanton	Mercer	ND	PSOC - 246
Sub-bituminous A	Adaville I	Elkol	Kemmerer	Lincoln	WY	PSOC - 248
High Volatile Bituminous A	Pittsburgh	Mathies	Thomas	Washington	PA	PSOC - 293
Low Volatile Bituminous	Lower Kitting	Cambria No. 33	Ebensberg	Cambria	PA	PSOC - 126
Anthracite	Buck Mountain	Reminger	Zerba	Schuylkill	PA	PSOC - 080

* In the case of lignite (PSOC-246), which was very extensively fractured, it was necessary to coat the original (large) lump with Koldmount resin before cutting it.

**From Vernon-Benshoff Co., 413 N. Pearl St., Albany 1, N.Y.

†From Buehler Ltd., 2120 Greenwood St., Evanston, Ill. 60204.

In addition, in order to ascertain the homogeneity of the particular vitrite micro-lithotype upon which the hardness studies were performed (see Section II C below), a similarly oriented thin section of PSOC-293 was prepared. This was viewed in transmitted white light, with the results discussed in Section III A below. The steps involved in its preparation were as follows.

- (i) Cut a rectangular slab, about 2 x 2 x 4 cm in size and so oriented as to have one long face parallel to the bedding plane and the adjacent long face perpendicular to it, from a larger lump of PSOC-293 with a water-cooled diamond saw.
- (ii) Dry grind the long surface perpendicular to the bedding plane on 220 grit SiC paper.
- (iii) Wet grind the same surface, first on 600 grit SiC paper and then on a fine Belgian hone (a fine grained, slightly metamorphosed, silica-based sedimentary mudstone having an unusually even and unstratified texture), until it exhibits a dull, even finish when observed under a shielded electric light.
- (iv) Dry the slab and glue it (ground surface downwards) onto a glass slide with a thin layer of APCO* cement.
- (v) Slice off three quarters of the slab of coal with a water-cooled diamond saw, leaving approximately 0.5 cm of coal glued onto the glass slide.
- (vi) Grind away further coal on a (dry) 220 grit SiC grinding wheel until only about a 30 μ m layer remains and the macerals sporinite and resinite appear red when the slide is held against a shielded 75 watt electric light bulb.
- (vii) Further wet grind on a coarse Belgian hone until the coal layer is translucent over 50% of its area.
- (viii) Complete the grinding process by wet grinding on a fine Belgian hone sharpened with 600 grit SiC until individual macerals show uniform translucency and good color contrast.
- (ix) Heat the slide to 190-200°F (88-93°C) and place over the coal a glass cover slide coated with a semi-hardened layer of Canada balsam.
- (x) Remove the excess Canada balsam, wash the slide with Joy detergent, and rinse and dry it.

Finally, to ensure that results obtained from the chosen test coals were of general applicability, and not merely manifestations of some property and/or characteristic unique to these coals, a few (grinding) tests were also performed on four other coals. These were:

- (i) St. Nicholas Breaker - a Pennsylvania anthracite comparable with PSOC-080;
- (ii) Bethlehem Brookdale coal - a low volatile bituminous coal from the same Lower Kittanning seam as PSOC-126;
- (iii) Illinois No. 6 coal - a high volatile bituminous C coal from Victoria, Illinois;
- and (iv) Helena Coal - a high volatile bituminous A coal from the Upper Freeport Seam at Homer City, Pennsylvania.

*From Applied Plastics Corporation, 612 E. Franklin Ave., El Segundo, California 90245.
The actual mixture used was 2-3 drops of hardener per cm³ of APCO R-313 resin.

Since these coals were only of secondary importance to the present work, no detailed characterization studies were performed on them. However, Illinois No. 6 coal has previously been studied by the PSU Coal Research Station under the designation PSOC-022 with the result that its properties have been well defined. The appropriate data sheets are included as Appendix II.

B. Environments

Surprising though it may at first sight seem, the choice of the environments employed in this work was not regarded as critical. This is because current understanding of chemomechanical effects implies that any environment which produces a given surface charge (i.e., transfers a given number of electrons to or from the solid surface) has essentially the same effect on near-surface flow and fracture behavior. The aim, therefore, was merely to use two series of environments that (i) were either known or could reasonably be expected to give rise to a wide range of zeta potential (surface charge), (ii) included several of the liquids previously discovered to exert some significant effect on the surficial mechanical behavior of coal and/or other materials, and (iii) were sufficiently different from one another to ensure the generality of the results. This latter condition was ensured by choosing one series of environments to be organic and the other aqueous. Finally, moist air and distilled water environments were also included to provide "base-line" data.

The organic environments chosen were reagent grade long chain primary alcohols. These go far towards meeting all the desired criteria in so far as (i) their ionization potentials decrease systematically with their molecular chain length ⁽⁶⁾, (ii) they have previously been shown to affect either the surficial mechanical behavior ⁽⁷⁻¹²⁾ and/or the zeta potentials ^(2,7,12) of various materials (both organic and inorganic) in a manner that varies systematically with their chain length, and (iii) one of their number causes chemical comminution of coal ^(13,14)

The inclusion of aqueous environments in the work served not only the scientific purposes already discussed, but also the practical need to investigate potential grinding aids at once less costly and less noxious than long chain alcohols. And in this respect it should be noted that aqueous environments occur in such variety that there is always a reasonable chance of finding one that not only gives the requisite zeta potential, but also is cheap, non-toxic, bio-degradable and non-polluting. A further reason for including these latter environments was that all of the coals studied contained significant amounts of water anyway (ranging in the five principal coals "as received" from 0.7 w/o (PSOC-126) to 34.1 w/o (PSOC-246), Appendix I).

The specific choice of the aqueous environments employed was guided, at least initially, by the work of Campbell ⁽¹⁵⁾, who studied the effect of pH on the zeta potentials of both whole Pittsburgh seam coal (presumably similar to PSOC-293) and its constituent lithotypes. Some of his data are shown in Figure I, and reveal that vitrain exhibits a point of zero charge at pH 3.7 and its maximum and minimum zeta potentials at pH 3.2 and 9.0, respectively. Consequently, aqueous HCl solutions of pH 3.2 and 3.7 and aqueous NaOH solutions of pH 9.0 were employed at the outset of this work. These were made up as required immediately prior to use, using reagent grade chemicals and distilled water having a conductivity of $<0.1 \mu\text{mho/cm}$.

It was found, however, that the pH values of these relatively dilute solutions changed slowly (~ 1 pH unit/day) during the course of any hardness determination in which they were employed, and at least an order of magnitude more rapidly when they were used in drilling rate, grinding rate and streaming potential studies--presumably because the greater surface area exposed in the latter experiments allowed faster leaching of some species from the coal. Accordingly, the drilling

and grinding studies (but not the hardness measurements) were repeated in buffer solutions having the same pH values. These latter solutions, which were also made up from reagent grade chemicals and distilled water having a conductivity $<0.1 \mu\text{mho/cm}$, had the following compositions:

- (i) pH 3.2 and 3.7 - 0.1M potassium hydrogen phthalate ($\text{KHC}_8\text{H}_4\text{O}_4$) + sufficient 0.1M HCl to give the desired pH;
- and (ii) pH 9.0 - 0.025M borax ($\text{Na}_2\text{B}_4\text{O}_7$) + sufficient NaOH to give the desired pH.

Streaming potential studies could not, of course, be carried out in these buffer solutions because of their high conductivities.

Further, because aqueous solutions of various sodium sulfonates have been reported as significantly affecting the grindability of coal ⁽¹⁶⁾, various strength solutions of one such salt were also included in the present work. The specific salt employed was a pale monofunctional alkyl aryl sulfonate prepared by Shell Oil Co. and having a long paraffinic chain attached to an aromatic naphthenic nucleus. It had a chemical formula approximating to $\text{C}_n\text{H}_{(2n-10)}\text{SO}_3\text{Na}$, with $n = 25-30$, and was supplied as a 62 w/o solution in an unspecified paraffinic hydrocarbon oil to which some 3-5 w/o of water had been added (presumably at the time of manufacture).

Finally, a few grinding studies were also carried out in dilute aqueous solutions of Aerosol OT* (di-octyl sodium sulfosuccinate, $(\text{CH}_2\text{COOC}_8\text{H}_{17})_2\text{SO}_3\text{Na}$, a widely used wetting agent).

C. Microhardness Measurement

A standard Leitz Miniload Hardness Tester was used to make quasi-static measurements of Vickers microhardness as a function of environment. These measurements were made on carefully mechanically polished surfaces of specimens oriented either parallel or perpendicular to the bedding plane. Several factors were taken into account in selecting the precise experimental conditions adopted. These are discussed below.

The first factor is the heterogeneous nature of coal, which requires that successive indentations be made at microstructurally equivalent locations if reproducible results are to be obtained. And in this context it should be noted that such reproducibility was at a premium in the present search for (possibly small) differences in hardness produced by environmental influences. Accordingly, all indentations were made in one particular microlithotype-vitrite. There were a variety of reasons for this choice: first, vitrite consists (by definition) of more than 95 v/o pure vitrinite, so that working with vitrite is almost as good as working with a single maceral; second, vitrite is readily identifiable under the optical microscope, even under the poor contrast conditions sometimes obtaining in environments of unsuitable refractive index and/or poor transparency; and third, vitrite is at once the most abundant and the most important of the microlithotypes occurring in the coals of the northern hemisphere, comprising as it does some 40-50% of their total mass ⁽¹⁷⁾. (Note that the vitrinite contents of the five principal coals included in this program ranged from 70 to 82 w/o (76-96 v/o)).

Two further considerations were that: (i) it was desired to work on regions of sufficient size, perfection and homogeneity that it was possible to make many indentations without ever having to place the indenter closer than 3-5 impression diameters to the edge of the region, to another indentation, to a pre-existing fracture, or to a mineral inclusion; and (ii) it was desired to obtain well-defined, permanent and relatively crack-free impressions

* From Fisher Scientific Co., 711 Forbes Ave., Pittsburgh, PA 15219

Figure I The zeta potentials of whole Pittsburgh seam coal and its constituent lithotypes in aqueous HCl and NaOH environments (from Campbell⁽¹⁵⁾).

that could be measured with the minimum of ambiguity. Accordingly, a preliminary series of indentations was made to see which of the chosen coals best satisfied these latter two criteria. This showed that the extensive fracturing accompanying the drying of the lower rank coals (PSOC-246 and 248) made these unsuitable to work with. Moreover, the hardness impressions obtained in the vitrites contained in these coals were difficult to see under the microscope (and it was not possible to use the coal petrologist's technique of coating the coal surface with soot prior to indentation because the present work was carried out under liquid environments). Likewise, it proved difficult to work with the two highest rank coals (PSOC-126 and 080) because the former gave rise to badly fractured hardness impressions and the latter deformed elastically (i.e., reversibly) rather than plastically (i.e., permanently) and so failed to give rise to permanent impressions. As a result it was elected to carry out the hardness studies on the vitrite microlithotype occurring in the medium rank high volatile bituminous A coal designated PSOC-293.

The fourth consideration dictating the experimental methodology adopted was the working hypothesis that the chemomechanical phenomena sought in this work derive from the chemisorption of (one or more) particular species from the test environment at the surface of the coal. This necessitated ensuring that nothing other than this (these) species gained access to the surface indented, at the least until the process of indentation was complete--a condition that was achieved by actually creating the test surface under the chosen environment and keeping it continuously and fully immersed therein throughout the hardness test procedure. In the case of a crystal that can be cleaved specimen preparation under this latter constraint poses few problems, but for coal--where the test surfaces must be mechanically polished to a high degree of perfection--the process becomes very time-consuming.

In addition, it was desired to use the smallest load consistent with accurate and reproducible measurement of the hardness in order to maximize the surface-to-volume ratio of the deformed region and thereby to maximize also any surficial environmental influence. And it was desired also to use a loading time that was on the one hand long enough both to eliminate any effects of the dynamics of the test procedure and to permit any environmental effect to develop, but on the other hand not so long as to make the performance of the requisite large number of tests an impossible task. For these latter two reasons, preliminary investigations were made of the effects of both load and loading time on hardness; and on the basis of these investigations, which are reported in Section IIIB below, values of 10 gm and 15 sec, respectively, were selected.

Hence, the specimen preparation procedure adopted in these hardness studies was as follows.

(i) Cut blocks oriented either parallel or perpendicular to the bedding plane from larger lumps with a diamond saw, and then mount these blocks in Koldmount resin and wet polish them down to 400 grit as per steps (i) to (iii) in the preparation of polished (megascopic) sections described in Section IIA.

(ii) Clamp the mounted and (rough) polished specimens in the mounting rings of a Buehler* Vibromet wheel polisher (Figure II).

(iii) Mount 600 grit SiC paper on the wheel of the polisher and fill it to a depth of several cm with the chosen environment.

* From Buehler Ltd., 2120 Greenwood St., Evanston, IL 60204

Figure II. Buehler Vibromet wheel polisher and mounting rings, with two of the latter upturned on the rim of the polisher to show the type of coal samples polished.

(iv) After polishing for 10 minutes, remove each specimen from the polisher face downwards in a shallow (1 cm deep) petri-dish full of the chosen environment, making the transfer to the petri-dish entirely beneath the surface of the pool of test environment in the polisher.

(v) Repeat steps (iii) and (iv), first polishing for 45 min on Buehler Texmet cloth loaded with a slurry of $0.3\mu\text{m Al}_2\text{O}_3$ in the test environment and then for the same time on Buehler Microcloth loaded with similar slurry of $0.05\mu\text{m Al}_2\text{O}_3$ abrasive.

(vi) Transfer a polished specimen from its petri-dish to the specimen well in the flat, environment-filled plastic tray shown mounted on the hardness tester in Figures III and IV, again keeping the specimen fully immersed throughout the transfer operation. (Note that: (i) both the tray itself and the aluminum insert forming the specimen well were specifically designed to accomplish this transfer in the minimum volume of test fluid; and (ii) those parts of the microhardness tester (other than the indenter itself and the 40x objective used to measure the indentation) that came into contact with the environment were kept dry by wrapping them with Saran wrap (Figure IV)).

(vii) Select the area to be indented using the 10x and 40x objectives and the micrometer screws in the specimen stage, and set the load on the indenter to the requisite 10 gm.

(viii) Accurately focus the 40x objective on the target area, and then rotate it away and the indenter into its place without adjusting either the focus of the microscope or the (suitably pre-set) dashpot that controls the rate of fall of the indenter. Thereafter release the indenter to form the hardness impression, lifting it off the coal surface as soon as the dashpot lever ceases its travel. (This ensures that the indenter always starts its fall from the same height above the specimen surface, always falls at the same speed (at least until it comes into contact with the coal surface), and always has the same total time of contact with that surface. In all of the present work the dashpot was set to complete its total travel in 30 seconds. This meant that the indenter spent 15 seconds falling to the coal surface and 15 seconds in actual contact with it).

(ix) Rotate the 40x objective back into place, measure the hardness impression and calculate the Vickers Hardness Number (VHN).

(x) Repeat steps (vii)-(ix) inclusive for a minimum of 12 indentations, and calculate both the mean VHN so obtained and its standard deviation.

(xi) When this mean VHN differs significantly from the mean VHN obtained in air (i.e., the difference between the two means is greater than the sum of their standard deviations) repeat steps (vii) - (x) inclusive after removing the specimen from the environment and again after repolishing it in air.

(xii) Repeat steps (vii) - (xi) inclusive for the remaining specimens obtained at step (v).

Finally, it should be noted that each of the five principal test coals employed contained significant amounts of water "as-received" (ranging from 0.7 w/o in PSOC-126 to 34.1 w/o in PSOC-246, Appendix I). Hence, it can be argued that, notwithstanding the strenuous attempts made to avoid contamination of the test surface by atmospheric moisture during specimen preparation, such surfaces were invariably covered with moisture obtained from within the coal itself. And therefore it also can be argued that the elaborate specimen preparation techniques adopted were a waste of time and effort. Such arguments may well be correct; in any case they are impossible to refute conclusively. But neither do they tell the whole story. Remember that the purpose of this work was to search for environmental effects of

Figure III. Leitz Miniload microhardness tester and ancillary tray for making measurements in liquid environments.

Figure IV. Close up of test specimen mounted in the environment - filled test well and ready for indentation. Note the Saran wrap protecting certain exposed parts of the microhardness tester.

potential value in industrial coal grinding processes that consume moisture-containing feedstock; and remember also that removing this moisture would be costly and would produce concomitant hard-to-characterize changes in the structure of the coal. Then note that the microhardness test was included in this study because its simplicity and surface-sensitivity make it a delicate tool for the study of environmental effects, but that such a test is only directly comparable with environment-sensitive drilling and grinding tests when performed under more or less similar environmental conditions. Hence, it was desired to perform the present hardness tests under the same environmental conditions as the accompanying drilling and grinding tests--i.e., under conditions (such as might occur in an industrial grinding process carried out in a controlled environment) in which (moist) as-received coal is fractured in the test liquid and chemisorption at the newly-created surface proceeds in an uncontrolled manner. Whether it is water from the coal or (possibly more active) species from the greater supply of test environment present that actually chemisorb on the newly fractured surfaces it was not the intent of the present study to determine. Rather, all the lengthy specimen preparation procedure adopted was designed to do was to provide--by abrading and fracturing (i.e., polishing) the as-received coal in the test environment--the conditions necessary to simulate the appropriate "competition" between the various species possibly seeking to chemisorb on the coal.

The other question of interest in a practically oriented project such as this is whether or not any environment-induced change in near-surface mechanical behavior is a permanent effect. And it was in order to explore this question that step (xi) -- redetermining the hardness (in air) in any instance where there appeared to be some environmental effect both immediately after removing the specimen from the environment and (again) after repolishing it in air--was included in this program.

D. Drilling Rate Measurement

Drilling rate measurements were made on all five principal test coals in both aqueous and organic environments by means of the Dunlap precision rotary drill press shown in Figures V and VI. This bench type tool was adapted for this purpose by: (i) replacing the standard, manually operated, lever-type bit loading system with a wheel-and-axle system that applied a constant load of 2.5 kg to the bit; (ii) replacing the standard (flat) work table with a flat-bottomed cylindrical container inside which the specimen was clamped by means of four screws threaded horizontally through the sidewall; and (iii) the addition of a linear variable differential transducer (LVDT) system capable of measuring bit penetration to a depth of 5 cm with an accuracy of 1%. The output from the LVDT was fed to a strip chart recorder to provide a continuous graphical record of bit penetration versus time. Bit rotation speed was held constant at 790 rpm throughout.

All drilling was performed perpendicular to the bedding plane because this was found by experience to better average out the effects of microstructural inhomogeneity than did drilling parallel to this plane. Specimen preparation involved no more than cutting roughly rectangular blocks (typically 8x5x4 cm in size) from large lumps of coal with a water-cooled diamond saw, wet grinding the largest surfaces of these blocks (which were arranged to be parallel to the bedding plane) on a belt sander covered with 220 grit SiC abrasive paper until they were both smooth and accurately parallel to one another, and then clamping the blocks in the specimen container with the bedding plane normal to the axis of the drill bit.

Figure V. Overall view of the apparatus used in the drilling rate studies, showing (from left to right) the chart recorder, the peristaltic pump and its drive motor and control box, and the drill press with the LVDT, the bit loading system, the core bit and adapter, and the specimen holder in place.

Figure VI. Close-up of the drill press showing details of the bit loading system, the fluid flow system and the specimen holder.

Typically, it was found possible to drill about 20 0.64 cm (1/4") diameter holes in each block at separations of (say) 1-2 hole diameters without breaking out chunks of coal from between adjacent holes or otherwise interfering with the drilling process. Only in the case of the most friable of the test coals, the lignite PSOC-246, was any difficulty experienced in this respect. However, the tendency for large flakes to break off from the surface of this coal as drilling started was easily overcome by coating all four sides of each test block with a substantial layer of Koldmount self-curing resin before clamping it in the specimen container.

Regardless of the details of its preparation, however, each and every block of coal was drilled according to the same sequence. First, three or four holes were drilled using distilled water as the drilling fluid. This served both as a check on the current state of bit wear and as a check on the variation of successive blocks one from another. Thereafter, five or so holes were drilled in each of successive test environments until the whole block was used up.

The first drilling experiments performed were simple puddle-type experiments in which conventional tool steel twist bits of 0.64 cm diameter were employed. In these studies the specimen was first immersed in the chosen test environment and the bit was then simply lowered gently on to it and set rotating. The environment was left to find its own way down the hole to the cutting zone against the flow of drilling debris moving up the flutes of the bit. However, owing primarily to the rapid and excessive wear exhibited by these bits, very non-reproducible results were obtained with this approach. Hence, these experiments were quickly abandoned and the system shown in Figures V and VI adopted instead.

This latter system, which was used to generate all of the drilling data presented in this report, uses a small peristaltic pump to force the environment down to the cutting zone along the hollow axis of a diamond-loaded core bit* having internal and external diameters of 0.41 and 0.64 cm, respectively (Figure VII). These bits, which were loaded with some $10^2 - 10^3$ diamond particles (of up to 200-300 μ m in size) plus substantial quantities of finer WC particles per cm^2 of cutting surface, were found to wear well and to give acceptably reproducible penetration rates over thousands of holes provided that they were properly cleaned after each hole was drilled. This reproducibility was demonstrated for the single bit used in the vast majority of the present drilling studies by using it to drill five holes in a particular "master-block" of PSOC-293 in a distilled water environment after every 100 or so holes drilled in other coals in other environments, and showing thereby that the average drilling rate obtained in the master block was always the same to within about one standard deviation (see Section IIIC).

In contrast, it was not found possible to readily maintain constant the rate of flow of the drilling fluid. The problem was that, for a given speed of rotation of the peristaltic pump, the flow rate decreased steadily with increasing bit penetration due to the concomitant increase in the length and the constriction of the fluid flow path. Moreover, the rate of this decrease in flow rate differed from one combination of coal and environment to another--presumably because of the different fracture characteristics of the several coals involved and of the different wetting characteristics of each in one environment as opposed to another. Hence, in all of this work the procedure adopted was to keep the peristaltic pump running at constant speed. This meant that the flow rate typically decreased from $\sim 1.5 \text{ cm}^3/\text{sec}$ when the bit was first placed on the surface of the coal to $\sim 1 \text{ cm}^3/\text{sec}$ when it reached a depth of 2-3 cm.

* A Metoram core bit from Hoffman Diamond Products, Inc., 108 Cedar St., Punxsutawney, PA 15767

Figure VII. Metoram diamond core bit.
Magnification 40X.

Under these conditions, the diamond core bits penetrated the coal at a rate that was almost independent of time (or depth drilled) (see Section IIIC). Accordingly, the absolute drilling rate (in cm/sec) was calculated from (the inverse of) the time required for the bit to penetrate from a depth of 0.610 to 1.525 cm. Such a definition of drilling rate not only serves to eliminate any transient effects taking place as the bit starts up, but also holds as nearly constant as possible the effects of friction, changing fluid flow rate etc. Also calculated was a normalized drilling rate defined as the ratio of the absolute drilling rate to the absolute drilling rate obtained in the same block in water. This latter parameter was introduced for two reasons: first, because it compares drilling rates in different environments at as nearly the same point in bit life as possible and should therefore be relatively insensitive to bit wear; and second, in order to provide a basis for comparing drilling rates obtained from blocks containing different distributions of pre-existing flaws. In the event, as the drilling rate measurements made in the master block of PSOC-293 show (Section IIIC), this first concern proved to be of no consequence because bit wear was not a problem.

E. Grinding Rate Measurements

(i) Overview

Two series of grinding experiments were carried out, one using a Hardgrove grindability tester, Figures VIII and IX, and the other a 19.5 cm (internal) diameter ball mill, Figures X and XI.

The former series involved three different kinds of tests. First, the standard Hardgrove Grindability Index (HGI) of each of the nine coals listed in Section IIA was determined (in a moist air environment) according to ASTM Standard No. D409-71. Next, a slightly modified version of this procedure was used to determine the same parameter for almost every combination of the five principal test coals listed in Table I and the environments listed in Section IIB. Moreover, in both of these sets of tests the ground coal was not merely screened at 200 mesh (75 μ m), which is all that is required for determination of the HGI, but rather was subjected to a full sieve analysis in order to see whether or not the grinding environment affected the particle size distribution of the ground product. And finally, the Hardgrove grindability tester was used in a series of short grinding time studies designed to explore the effects of (i) coal rank and (ii) environment on the primary daughter fragment distributions obtained during grinding. The first of these studies used PSOC-126, -248 and -293, Illinois No. 6 coal and St. Nicholas Breaker in moist air environments, and the second PSOC-246 and Helena coal in moist air, distilled water and methanol environments. In contrast, the series of experiments utilizing the ball mill involved only a short study of the effects of moist air, distilled water, methanol, butanol and aqueous sodium sulfonate and Aerosol OT environments on the specific rates of breakage of PSOC-293 and Bethlehem Brookdale coal, and of the effects of the first four of these environments on the specific rate of breakage of St. Nicholas anthracite. These various tests are described in greater detail in Sections IIE (iii), (iv), (vi) and (vii) below.

Figure VIII. Hardgrove grindability tester.

Figure IX. The grinding bowl of the Hardgrove grindability tester with its upper grinding ring lifted out to show the eight 2.54cm diameter steel balls it employs as the grinding medium.

Figure X. 19.5 cm diameter ball mill in place on driving rolls.

Figure XI. 19.5 cm diameter ball mill opened up to show the 2.67 cm diameter steel balls it employs as the grinding medium.

(ii) Apparatus

The Hardgrove grindability tester is shown in the foreground of Figure VIII. It consists of a cast iron frame to the underside of which is clamped a cast iron grinding bowl (shown separately in Figure IX), and on the top side of which are mounted an integral reduction gear box and electric motor (partly hidden by the gear box in Figure VIII) and a control unit consisting of a revolution counter and a device for automatically switching off the motor after a set number of revolutions (60 in the present work). A vertical shaft, which passes through the frame via a grease seal situated midway between the control unit and the gear box, transmits the 20 rpm rotation delivered by the latter to the upper grinding ring - which ring rests horizontally on eight 2.54 cm diameter steel balls lying in a coal-filled horizontal circular track in the bottom of the grinding bowl (Figure IX). This same shaft also transmits a vertical load of 29 kg to the balls via the upper grinding ring. Hence, when the motor is switched on the balls are rolled over and caused to crush the coal lying in the bottom of the grinding bowl.

The ball mill, Figures X and XI, is a much simpler piece of equipment consisting of a muffled steel cylinder (diameter 19.5 cm, length 17.5 cm, volume 5225 cm³) openable at one end and having six full length 5mm wide x 2mm high rectangular cross-section steel lifters equally spaced around its inner circumference. In operation the cylinder is simply loaded with the desired charge and grinding medium, closed, placed horizontally on the variable speed, motor driven, rubber coated table rolls shown in Figure X, and tumbled at the desired speed for the desired time. The rolls are switched off at the appropriate moment by an automatic timer.

(iii) Conventional HGI Determinations

In each standard Hardgrove test 50 gm of -16 to +30 mesh (1.18 to 0.600 mm) coal (prepared from larger lumps by jaw and/or roll crushing and screening) was ground for 3 minutes (i.e., for 60 revolutions of the upper grinding plate) before being transferred to a vertically nested stack of standard 8" (20 cm) screens (Nos. 16, 20, 25, 30, 50, 70, 100, 140, 200, 270, and 400, having nominal openings of 1.18, 0.850, 0.710, 0.600, 0.300, 0.212, 0.150, 0.106, 0.075, 0.053, and 0.038 mm, respectively) and sieved with a Ro-Tap Testing Sieve Shaker for a total of 20 minutes. This sieving operation was interrupted after 10 minutes, and again after 15 minutes, to brush off any material clinging to the underside of each screen into the one below, and this same procedure was also carried out at the end of the operation. Each size fraction was then weighed to obtain the size distribution of the ground material, and the HGI was calculated from the (empirical) formula

$$\text{HGI} = 13 + [6.9(50 - W)],$$

where W is the total weight of material retained on the 200 mesh and larger screens. Tests in which the total loss of coal during transfer from the grinding bowl to the screens and during sieving exceeded 0.75 gm were ignored. And in the tests where the weight loss was acceptable, the lost material was assumed to have come entirely from the -400 mesh fraction.

(iv) HGI Determinations in Liquid Environments

To determine the HGI in a liquid environment, the procedure described in Section IIE (iii) above was modified in several respects. First, the 50 gm of -16 to +30 mesh coal used was added to the grinding bowl in the form of a freshly-mixed slurry containing 45v/o coal and 55v/o liquid. The only exceptions to this procedure were the cases of PSOC-126 and PSOC-293 in methanol and butanol environments, for which parallel measurements were carried out using both freshly made slurries and slurries that had been allowed to "age" for 2 hr prior to grinding. Second, the ground materials were wet sieved and then (for all but two environments) air-dried at room temperature before weighing to determine their size distributions and HGI's. The two anomalous environments were the two longest chain alcohols employed (octanol and dodecanol), both of which dried so slowly at room temperature that it was necessary to accelerate this process by heating to $\sim 50^\circ\text{C}$ in order to complete the work in a reasonable time. Dodecanol (melting point 26°C) also posed the further problem that it tended to solidify when it came into contact with the grinding bowl. Accordingly, when using this environment the grinding bowl, the eight steel balls, and the upper grinding ring were all preheated. This was accomplished by soaking these components in hot water and then quickly drying them off before adding the slurry and starting the test. As a result, the experiments in dodecanol environments were not carried out at room temperature, but at some unknown (and continuously varying) temperature in the range of $50 - 25^\circ\text{C}$. Finally, the HGI determinations performed in liquid environments differed from those carried out in air in that wet sieving almost invariably produced much larger losses of fine material than did dry sieving. For this reason losses as large as 3-4 gm were routinely accepted, and accounted for by adding the missing material to the -400 mesh fraction.

(v) B & S Values: Theoretical Considerations

The HGI determinations discussed in the two preceding sections are purely empirical comparisons of the grinding behavior either of different coals in the same environment or of the same coal in different environments. And, as such, it was only important that the tests be carried out in a consistent manner. However, the experiments described in the next two sections are concerned with (the effects of environment on) two much more fundamental measures of grinding performance - the primary daughter (progeny) fragment distribution function ("B values") and the specific rate of breakage or selection-for-breakage parameter ("S value") for particles of a particular size (i.e., lying in a particular narrow size interval). To understand these experiments fully, therefore, it is necessary both to define these parameters precisely and to consider the problems involved in determining them experimentally. These tasks are taken up in this section.

Suppose, then, that the suffix $i = 1, 2, \dots, n$ designates n successively smaller size intervals, each identified by its upper size limit; and let $w_i(t)$ be the weight fraction of material of size i (i.e., lying in size interval i) after grinding for time t . In addition, let $P_i(t)$ be the total fraction by weight of material of size i or smaller at time t . It follows that

$$P_i(t) = \sum_{j=i}^n w_j(t), \quad (1)$$

and hence that

$$P_1(t) = \sum_{j=1}^n w_j(t) = 1 \quad (2)$$

and

$$P_n(t) = w_n(t). \quad (3)$$

Further, let $b_{i,j}$ be the fraction by weight of material of size i produced when particles of size j break, it being assumed that breakage necessarily transfers material into at least the next smallest size interval. And let $B_{i,j}$ be the total fraction by weight of material of size i or smaller produced when particles of size j break. It then follows that $b_{i,j}$ and $B_{i,j}$ are defined only for $i \geq j$ and that

$$\sum_{i=j+1}^n b_{i,j} = 1, \quad (4)$$

$$B_{i,j} = \sum_{k=i}^n b_{k,j} = 1 \text{ if } i = j+1, < 1 \text{ if } i > j+1, \quad (5)$$

and
$$b_{i,j} = B_{i,j} - B_{i+1,j} \quad (6)$$

Now, consider a one size fraction sample having an initial size distribution defined by

$$\begin{aligned} w_1(0) &= 1, \\ w_2(0) &= w_3(0) = \dots = w_n(0) = 0, \end{aligned} \quad (7)$$

or by the equivalent equations

$$\begin{aligned} P_1(0) &= 1, \\ P_2(0) &= P_3(0) = \dots = P_n(0) = 0. \end{aligned} \quad (8)$$

And suppose that this sample is ground for a time δt sufficiently short that none of the fragments produced by breakage of an original particle is broken again. In this situation, the amount of material removed from size interval 1 by breakage is $1 - w_1(\delta t)$, and the amounts added to size intervals 2, 3, ..., n are $w_2(\delta t)$, $w_3(\delta t)$, ..., $w_n(\delta t)$, respectively. Hence, in the limit as $\delta t \rightarrow 0$, the primary daughter fragment distribution is defined by

$$b_{i,1} = \frac{w_i(\delta t)}{1 - w_1(\delta t)}, \quad i = 2, 3, \dots, n, \quad (9)$$

or (in equivalent cumulative form) by

$$B_{i,1} = \frac{P_i(\delta t)}{P_2(\delta t) - P_2(0)}, \quad i = 2, 3, \dots, n. \quad (10)$$

The specific rate of breakage of particles of size i , S_i , may be understood by considering the change in either $w_i(t)$ or $P_i(t)$ with t . Obviously, the rate of change of $w_i(t)$ is simply the difference between the rate of production of fragments of size i (by breakage of particles in sizes 1 through $i-1$ inclusive) and the rate of breakage of particles in size i (into fragments of sizes $i+1$ through n inclusive). Thus,

$$\frac{dw_i(t)}{dt} = -S_i w_i(t) + \sum_{j=1}^{i-1} b_{i,j} S_j w_j(t) \text{ if } i = 2, 3, \dots, n-1, \quad (11)$$

$$\frac{dw_i(t)}{dt} = -S_i w_i(t) \text{ if } i=1, \quad (12)$$

and

$$\frac{dw_i(t)}{dt} = \sum_{j=1}^{i-1} b_{i,j} S_j w_j(t) \text{ if } i=n. \quad (13)$$

And, equally obviously, the rate of increase of $P_i(t)$ is simply the rate of production of fragments of size i and smaller by the breakage of particles of size $i-1$ or larger, so that

$$\frac{dP_i(t)}{dt} = \sum_{j=1}^{i-1} \sum_{k=i}^n b_{k,j} S_j w_j(t) \quad (14)$$

$$= \sum_{j=1}^{i-1} B_{i,j} S_j [P_j(t) - P_{j+1}(t)] \text{ if } i = 2, 3, \dots, n \quad (15)$$

and

$$\frac{dP_i(t)}{dt} = 0 \text{ if } i = 1. \quad (16)$$

In the particular case $i = 1$, equation 12 gives

$$\frac{dw_1(t)}{dt} = -S_1 w_1(t), \quad (17)$$

or

$$\ln[w_1(t)] = -S_1 t + \ln[w_1(0)]. \quad (18)$$

It follows that when first order breakage occurs (i.e., the S_i are constants), S_1 can be found from the slope of the (straight line) plot of $\ln[w_1(t)]$ versus t .

In reality, however, the experimental determination of $b_{i,1}$ or S_1 poses certain difficulties. The first is that the holes in a sieve are not all exactly the same size, so that increasing the sieving time increases the probability of any particle finding (and falling through) those holes that are larger than average. This problem is best overcome by (empirically) choosing a particular sieving schedule and sticking to it (as was done in the HGI determinations).

A second difficulty is that the act of sieving itself causes a certain amount of comminution. This problem could be (and was) ignored in the comparative HGI determinations, but has to be taken into account in the measurement of $b_{i,1}$ or S_1 . The solution is to perform a "blank analysis" - i.e., to sieve a sample of the feed material according to the chosen sieving schedule and see how its size distribution changes. Such experiments reveal that the effect of screening on an one size fraction sample typically is to transfer some weight fraction δ (the so-called "sieving error") of material to the next size interval - i.e., to convert the size distribution from equations 7 and 8 to

$$\begin{aligned}
 w_1(0) &= 1-\delta, \\
 w_2(0) &= \delta, \\
 w_3(0) = w_4(0) = \dots = w_n(0) &= 0,
 \end{aligned} \tag{19}$$

or

$$\begin{aligned}
 P_1(0) &= 1, \\
 P_2(0) &= \delta, \\
 P_3(0) = P_4(0) = \dots = P_n(0) &= 0.
 \end{aligned} \tag{20}$$

It is for this reason that the semi-log plots of $w_1(t)$ versus t used in the determination of S_1 are drawn through the point $(1-\delta, 0)$ rather than $(1, 0)$.

The third difficulty that must be taken into account is that the breakage of a brittle material such as coal during grinding is dependent on the way in which the feed material is prepared. This is a reflection of the fact that the mechanical properties of brittle solids are determined by the flaws they contain, many of which are introduced during sample preparation. Like the sieving error, this problem could be (and was) ignored in the comparative HGI studies. And, because it is merely a transient effect, it can also be ignored in the (relatively) long grinding time studies involved in the determination of S_1 . Conversely, however, it cannot be ignored when measuring $b_{i,1}$ values, for this measurement involves only short grinding times. In this case, the solution is to start with a substantial quantity of one size fraction feed, grind briefly, screen to determine the resultant size distribution, calculate $b_{i,1}$ for each i , grind the remaining top size fraction material for a further short interval, screen again, recalculate $b_{i,1}$ for each i etc. until the $b_{i,1}$ values converge.

Finally, it also needs to be recognized that, desirable though it is to reduce the grinding time and thereby reduce the secondary breakage in any determination of $b_{i,1}$, such a reduction also reduces the extent of primary breakage and therefore makes it more difficult to obtain accurate sieve analyses from which to calculate $b_{i,1}$. As a result, the usual procedure is to compromise - grind for long enough to produce 15-25% primary breakage and then make some sort of more or less approximate correction for secondary breakage when calculating $b_{i,1}$.

The method of correction used in this work was the "B_{II} method"⁽¹⁸⁾, which begins with the assumption that the quantity $B_{i,j}S_j$ is a function of i only and not of j - i.e., that the amount of broken material falling into size i as a result of the breakage of larger particles is independent of the size of those particles. Physically this is not entirely unreasonable because of the compensation effect - the tendency for larger particles to break faster and to throw a lesser proportion of their daughter fragments into the finer sizes as compared to smaller particles. When such compensation is exact, equation 15 reduces to

$$\frac{dP_i(t)}{dt} = B_{i,j}S_j [1 - P_i(t)], \quad i = 2, 3, \dots, n, \tag{21}$$

which can be integrated to obtain

$$1 - P_i(t) = [1 - P_i(0)]e^{-B_{i,j}S_j t}, \quad i = 2, 3, \dots, n. \tag{22}$$

Now, suppose that the feed is the one size fraction sample with sieving error δ defined by equations 19 and 20. It follows from equation 22 that

$$1 - P_2(t) = (1 - \delta)e^{-S_1 t}, \tag{23}$$

since $B_{2,1} = 1$ by definition (cf. equation 10). Hence,

$$-S_1 t = \ln [(1-P_2(t))/(1-\delta)] \quad (24)$$

In addition, setting $j = 1$ in equation 22 gives

$$1 - P_i(t) = [1 - P_i(0)]e^{-B_{i,1} S_1 t}, \quad (25)$$

or

$$-B_{i,1} S_1 t = \ln[(1 - P_i(t))/(1 - P_i(0))], \quad (26)$$

which latter may be combined with equation 24 to give

$$B_{i,1} = \frac{\ln[(1 - P_i(t))/(1 - P_i(0))]}{\ln[(1 - P_2(t))/(1 - \delta)]} \quad (27)$$

It is from this equation that the $B_{i,1}$ ($i = 3, 4 \dots n$) values reported herein were calculated.

(vi) Determination of B Values

To determine $B_{i,1}$ values in moist air environments approximately 100gm of -16 to +20 mesh (1.18 to 0.850 mm) coal was prepared by jaw and/or roll crushing and screening, sieved for 20 min (using the same Ro-Tap Testing Sieve Shaker and stack of nested 8" (20cm) screens as used in the HGI determinations (Section II E (ii))) to determine δ (typically ~ 0.05), ground in the Hardgrove grindability tester for a short time (2-10 sec, depending on coal rank), and sieved according to the same procedure to determine the size distribution resulting from grinding. An initial set of $B_{i,1}$ values was then calculated from these size distribution data by the B_{II} method of data analysis outlined above. Thereafter, this sequence of events was repeated two or three more times, each time using as feed that fraction (approximately 75-80 w/o) of top size (-16 to +20 mesh) material surviving from the previous iteration. In such a sequence, each iteration tends to precondition the feed to the next, so the $B_{i,1}$ values typically converged in two or three iterations to numbers characteristic of the breakage in the Hardgrove tester and independent of the original method of specimen preparation.

To study the effects of liquid environments on $B_{i,1}$ values, the above procedure was modified in two respects. First, the feed was changed to variously aged slurries containing 60 v/o coal and 40 v/o liquid; and second, screening was carried out wet (i.e., in the grinding environment). In addition, the $B_{i,1}$ values characteristic of PSOC-246 and the Helena coal used in this part of the work were determined in moist air environments by means of a "hybrid" experimental technique that involved grinding in moist air and screening in distilled water. The idea of this was to eliminate any difference due to a changeover from wet to dry screening from comparison of $B_{i,1}$ values in air and different liquid environments.

(vii) Determination of S Values

The S_1 determinations were all carried out in the ball mill shown in Figures X and XI and described in Section II E (ii), using the so-called "Bond grinding conditions" - i.e., with the grinding medium (63 26.7 mm diameter stainless steel balls each weighing approximately 77.5 gm) and its internal porosity (the interstices between the balls) occupying 20% of the total volume of the mill, and the charge in uncompacted powder form (166 cm³ of - 20 to +30 mesh (0.850 to 0.600 mm) coal prepared by jaw and/or roll crushing and screening) occupying approximately one half of the volume of these interstices with the balls at rest. In those experiments involving liquid (as opposed to moist air) environments, 110 cm³ of the test liquid was also added to the mill, converting the charge into a slurry containing 45 v/o coal. In all cases

this slurry was allowed to age for 2 hr prior to commencing grinding. Throughout this work the mill was rotated at 70% of critical speed (73 rpm); and in every case the charge was preconditioned by grinding (in moist air) for 2-3 sec and then sieved (again in moist air) at 30 mesh for 20 min using the Ro-Tap Testing Sieve Shaker in order to make an estimate of δ . When grinding in liquid environments, the mill was first rotated for the desired time, and then the entire charge was dumped out, wet screened at 325 or 400 mesh to remove the fines, dried in an oven at 60 - 70°C, screened (again in moist air) at 30 mesh in the same manner as previously, and finally weighed to obtain $w_1(t)$. This meant that a separate sample was needed for each grinding time studied. In the experiments conducted in moist air environments, in contrast, only one sample of each coal was employed, and the mill was stopped periodically so that its contents could be sampled to determine $w_1(t)$. The sampling procedure adopted was simply to allow the fines to settle, open the mill, push the balls aside, spoon out about 25 gm of coal, screen this coal at 30 mesh in moist air as before, return the coal to the mill, and finally close the mill up so that grinding could continue. Only negligible amounts of coal were lost during this sampling procedure.

F. Zeta Potential Measurement

Relatively few zeta potential measurements were made for the simple reason that, even using the automated, rapid-cycling streaming potential apparatus specially built for this project (see Figures XII - XV), it required several days of streaming the environment to and fro through the porous plug sample before the streaming potential (and therefore the zeta potential) settled to a stable value. Consequently, zeta was measured only for each of the five principal test coals in methanol and for PSOC-293 in distilled water, aqueous HCl, ethanol, butanol and propanol environments.

The heart of the streaming potential apparatus is the cell shown in close-up in Figure XIV. This consists of two similar 500 cm³ capacity tapered Pyrex glass flasks fitted with identical electrodes and linked at their lower ends by a U-shaped Pyrex tube about 1 cm in diameter and 10 cm long. Snugly fitted into each end of this U-shaped tube is a Pt disc about 1mm thick and 1.9 cm in diameter that is extensively perforated with 2mm diameter holes and covered on its underside with 80 mesh (180 μ m) Pt - 10% Rh gauze. These discs, which form the lower ends of the electrode assemblies, are mounted on the ends of 16 cm long, 2.5 mm diameter Pt rods that are themselves recessed into the ends of 6.4 mm diameter stainless steel rods some 30 cm in length. And these latter rods in turn pass through 25 mm diameter Teflon electrode holders housed in Pyrex tubes that clamp to the tops of the 500 cm³ flasks. Both the joints between the electrode holders and their Pyrex housings and those between these same housings and the flasks are sealed by neoprene "O"-rings; and the stainless steel rods are sufficiently tightly fitted into their Teflon holders to render the joints between these components gas-tight also.

The cell and its electrodes, together with an Hg manometer that provides a ready visual indication of the pressure difference between the flasks, are electrically isolated inside a large (75 x 50 x 30 cm) housing made of light gauge Al sheet and gauze, and are linked to the rest of the apparatus only by three pairs of leads through this housing. One of the flasks does, however, contain an access port through which specimens of the test environment can be withdrawn for pH and/or conductivity measurements as required.

Figure XII. Front view of streaming potential apparatus showing general arrangement of cell, electrodes and mercury manometer.

Figure XIII. Side view of streaming potential apparatus showing pressure reservoir, drying columns, pressure regulator, timer and solenoid valves.

Figure XIV. Close up of cell and electrodes.

Figure XV. Schematic diagram of streaming potential apparatus.

One of the pairs of leads through the housing is 6.4 inside diameter Tygon tubing that links the flasks to a pressure transducer mounted in parallel with the Hg manometer. The output from this transducer is fed to a chart recorder to provide a permanent record of the pressure difference between the flasks. The second pair of leads is 6.4 mm outside diameter stainless steel tubing that connects each flask via a 3-way solenoid valve either to the gas flow system or to a vent to atmosphere. And the third pair is electrical wiring that connects the electrodes to a suitable voltmeter (either a Keithley Model 150B microvolt ammeter or a very high impedance ($\sim 10^{14}$ ohm) Keithley Model 610B electrometer). A suitable resistor is connected across these leads and can be switched in and out of the circuit by a timer that operates this switch in concert with the solenoid valves according to the schedule shown in Figure XVI. Basically, this timer operates on a 150 sec cycle during one half of which the resistor is in the circuit and during the other half of which it is not. And during each 75 sec half cycle each flask is alternately pressurized with (commercial purity) N_2 at a pressure of a few cm of Hg for 20 sec. and vented to atmosphere for 55 sec, it being arranged that the pressurization of each flask occurs during the middle 20 sec of the 55 sec for which the other flask is open to the atmosphere. The result is that during each half cycle the test liquid first flows through the porous plug from the right flask to the left for 20 sec, then stops flowing for 17.5 sec before reversing direction for 20 sec and finally stopping again for 17.5 sec.

The purpose of switching the resistor alternately in and out of the circuit on successive half cycles is to monitor any change in the conductivity of the environment that occurs during streaming. This is done indirectly and approximately by calculating the resistance R_p of the porous plug from the streaming potentials (E and E_p , respectively) obtained at a given driving pressure (and therefore at constant streaming current i) with and without the resistor R in the circuit. Ohm's law requires that

$$E_p = iR_p$$

and

$$E = iR',$$

where

$$1/R' = 1/R + 1/R_p.$$

Also,

$$R_p = \alpha l / \lambda A,$$

where l and A are the length and cross-section of the U-shaped tube, respectively, λ is the conductivity of the environment, and α is a correction factor that may be determined for any plug by measuring the resistance between the Pt electrodes in an environment of known conductivity. Hence,

$$\lambda = \frac{\alpha l E}{RA(E_p - E)}$$

The advantages of monitoring λ in this fashion rather than via conductivity measurements on samples of the test environment removed from the cell are two-fold. First, there is no need to stop or otherwise interrupt the experiment; and second, λ is monitored continuously and automatically rather than occasionally and manually. However, there is also a concomitant disadvantage - the fact that α (which is determined primarily by the plug geometry) tends to increase as repeated streaming packs the plug more and more tightly. For this reason, both methods of monitoring λ were employed in this work.

Figure XVI. Schematic diagram of timer schedule.

To make a zeta potential determination, the first steps are* to clean the cell and electrodes (the former by washing first in distilled water and then in methanol, and finally drying in air; the latter by washing in turn in aqua regia, dilute HNO_3 , distilled water and methanol, and then drying in air) and to prepare (by crushing, screening, washing many times in distilled water, and finally drying in air) a sufficient quantity of -18 to +45 mesh (1.000 to 0.355 mm) coal to completely fill the U-shaped tube. The electrodes are then used to pack this into as immovable a porous plug as possible. Next, the conductivity and (if applicable) the pH of the proposed test environment are measured, the former by means of a Hewlett-Packard No. 4270A automatic capacitance bridge operating at 1 kHz and the latter with a Sargent Welch Model PBX pH meter and combination electrode. Thereafter, each flask is filled somewhat less than half full with the environment of interest (so that (a) the environment never comes into contact with the stainless steel rods and (b) there can be no flooding if the flow becomes asymmetrical and all the liquid ends up in one flask), the N_2 is turned on and its pressure adjusted to the desired value, the cell is bled to expel air, the timer is switched on to start the liquid streaming, and the streaming potential, E_p or E_p , and the driving pressure, P , are recorded as functions of time for a period of several days. And periodically during this time the apparatus is stopped for 10 min or so in order that approximately 40 cm^3 aliquots of the test liquid can be removed temporarily from the apparatus to determine whether or not either their conductivity and/or their pH has changed. Then, after equilibrium has been reached and maintained for perhaps 24 hr., the N_2 supply is switched off ahead of the pressure reservoir and the system is allowed to "bleed-off" (i.e., run at continually decreasing pressure until the pressure in the reservoir falls to atmospheric). Finally, the zeta potential, ζ , is calculated from E_p and P by means of the formula

$$\zeta = \frac{\delta}{\epsilon \epsilon_0} \frac{\eta \lambda E_p}{P},$$

where (in RMKS units) $\delta = 1$, ϵ_0 (the permittivity of free space) = 8.854×10^{-12} farad/meter, ϵ is the (dimensionless) dielectric constant as given in Reference 6, η is the viscosity (in pascal sec) from the same source, λ is the conductivity (in siemen/meter), and E_p and ζ are both measured in volts. It will be noted that the above equation, which is based on the assumption that the flow in the capillaries of the porous plug is laminar, predicts that $E_p \propto P$. The purpose of the bleed-off experiment is to check this assumption.

III. RESULTS

A. Coal Petrography

Figures XVII - XXI show polished microscopic sections (oriented perpendicular to the bedding plane) of each of the five principal test coals in order of increasing rank (i.e., in the order PSOC-246, -248, -293, -126 and -080). It can be seen that microstructurally these coals fall into two groups. The three higher rank coals, PSOC-293, 126 and 080, Figures XIX to XXI, are all characterized by (i) relative freedom from cracks and (ii) microstructures composed of parallel bands of mono- and bi-maceral microlithotypes. In each case the monomaceral (vitrite) bands, which are recognizable by their bright appearance and their homogeneity, contain (by definition) more than 95 v/o vitrinite, and the bimaceral bands contain small amounts of inertinite and rather larger quantities of mineral matter dispersed in vitrinite.

* In some cases successive runs were made using the same porous plug. In these instances the apparatus was cleaned with the plug in place simply by multiply rinsing with the test liquid to be used in the next run.

Figure XVII. Megascopic section of PSOC-246 showing vitrinite containing inertinite and mineral matter. The shrinkage of this coal during preparation and its extreme friability make polishing extremely difficult. Magnification 200X.

Figure XVIII. Megascopic section of PSOC-248 showing an extensive network of fractures in a matrix of vitrinite containing particles of inertinite, exinite and assorted minerals. The extreme friability of this coal precluded polishing its surface flat enough to get it all in focus at the same time. Magnification 200X.

Figure XIX. Megascopic section of PSOC-293 showing bands of vitrinite (light grey), the central one of which contains small regions of inertinite (whitish) and assorted mineral inclusions (black). Magnification 200X.

Figure XX. Megascopic section of PSOC-126 showing large areas of vitrinite (light grey), some of which contain particles of inertinite (whitish) and/or mineral inclusions (black). Magnification 200X.

Figure XXI. Megascopic section of PSOC-080 showing two bands of vitrinite (light grey) containing mineral inclusions (black) and separated by a mineral free band of vitrite (that is essentially pure vitrinite). Magnification 200X.

In contrast, the two lower rank coals, PSOC-246 and -248, Figures XVII and XVIII, are both extensively cracked and both composed entirely of one bimaceral microlithotype (which again contains inertinite and mineral matter dispersed in vitrinite). These latter coals do, however, differ in that PSOC-248 exhibits a finer scale pattern of cracks than does PSOC-246.

Figure XXII shows a thin section of PSOC-293 that also is oriented perpendicular to the bedding plane. This reveals that vitrite is composed of distinguishable layers of vitrinite that appear to have a relatively isotropic fine structure. Note that little can be learned from a thin section about the network of cracks existing in a bulk coal because the thinning process tends to change this network and to add additional cracks. It is therefore not clear whether the cracks seen in Figure XXII were present in the original (bulk) coal or not.

B. Microhardness

The results of the Vickers microhardness studies are summarized in Figures XXIII - XXV and Table II. Figure XXIII shows microhardness impressions in one of the vitrite layers exposed in a polished section of PSOC-293 oriented perpendicular to the bedding plane. These indentations were made in air using a 10 gm load and a loading time of 15 sec. This figure reveals that, for this coal under these conditions at least, it is possible to obtain well-defined, permanent impressions that are crack-free and can be measured unambiguously. Note, however, that the edges of these impressions are sometimes slightly concave, showing that there is substantial residual elastic stress in the surrounding material. It is also apparent, both from Figure XXIII and from the standard deviations reported in Figures XXIV and XXV and in Table II, that individual vitrite layers in PSOC-293 are relatively homogeneous. And, perhaps surprisingly in view of the fact that PSOC-293 is a layered rather than an isotropic material, Table II reveals that in every environment investigated the hardness of vitrite is the same regardless of whether it is measured on surfaces oriented perpendicular to or parallel to the bedding plane. This presumably is a reflection of the fact (Figure XXII) that vitrinite has a more or less isotropic fine structure in this coal.

The multiple entries listed for particular environments in Table II and the multiple data points shown for particular loads in Figure XXV were variously obtained from different vitrite layers in the same specimen of PSOC-293 and from completely different specimens of this coal. Nonetheless, both these data and the data of Figure XXIV show remarkable overall consistency and only an occasional, obvious anomaly. It is therefore suggested that: (i) the properties of vitrite are substantially the same throughout PSOC-293; (ii) at least over the limited ranges of each explored, neither load nor loading time significantly affects the hardness of this vitrite; and (iii) the occasional anomalous data point is probably merely the result of mistakenly identifying the other major (bimaceral) microlithotype as vitrite. Further, as a corollary to (ii), it was decided that it was permissible in the bulk of the hardness studies to adopt as standard a 10 gm load (which gives great surface and environment-sensitivity) and a 15 sec loading time (which minimizes the time required to perform the experiments). It was also noted, however, that the occurrence of occasional anomalous results means that any measurement purporting to exhibit some influence of environment (or of any other factor) on hardness needs to be repeated in order to be sure that the influence is real. And it is for this reason that multiple hardness values are reported in Table II for methanol, butanol and aqueous sodium sulfonate environments and in Figure XXV for most loads.

Figure XXII. Thin section of PSOC-293 showing vitrinite (red brown), inertinite (black) and assorted fractures (white). Magnification 70X.

Figure XXIII. Hardness impressions in the vitrite constituent of PSOC-293.

Figure XXIV. The hardness of the vitrite constituent of PSOC-293 as a function of loading time.

Figure XXV. The hardness of the vitrite constituent of PSOC-293 as a function of load. Data points enclosed in a box were all obtained at the same load (defined by the center of the box) and have merely been displaced for clarity of presentation.

Table II. The Vickers microhardness of vitrite (kg/mm²)

Orientation of Surface Indented + Environment	In the Environment		In Air "Immediately" (i.e., ~ 1 Hour) After Removal From Overnight Immersion in the Environment		In Air Following Repolishing in Air ~ 1 Day After Removal From the Environment
	Parallel to Bedding Plane	Perpendicular to Bedding Plane	Parallel to Bedding Plane	Perpendicular to Bedding Plane	Perpendicular to Bedding Plane
Air	36.2 ± 0.8	36.9 ± 1.1			
Air		37.8 ± 1.8			
Air		36.0 ± 0.3			
Air		37.2 ± 0.7			
Air		36.0 ± 0.3			
H ₂ O	37.7 ± 1.0	40.0 ± 1.3	37.2 ± 0.9	37.3 ± 0.7	
HCl pH 3.2	36.9 ± 1.0	36.4 ± 0.9		37.1 *	37.8 *
HCl pH 3.7		36.9 ± 0.7		39.1 ± 0.9	37.2 ± 0.7
NaOH pH 9.0		33.4 ± 0.6		38.2 ± 0.7	
10wt % Na Sulfonate	29.9 ± 0.3	29.5 ± 1.0	37.8 ± 1.1		
1 wt % Na Sulfonate	29.9 ± 0.6	30.0 ± 0.3			
Methanol		30.3 ± 0.5		30.1 ± 0.7	37.6 ± 0.8
Methanol		30.1 *		40.2 *†	37.8 *
Methanol	28.0 ± 1.7 ⁺	30.5 ± 1.1 ⁺			
Ethanol	36.1 ± 1.0	36.3 ± 1.4			
Propanol	37.3 ± 1.1	36.8 ± 1.4			
Butanol	55.0 ± 1.0 ⁺	53.2 ± 1.3 ⁺	36.3 ± 1.0	36.5 ± 1.0	
Butanol	60.7 ± 3.8 ⁺	62.4 ± 7.1 ⁺			
Pentanol	35.8 ± 0.7	36.8 ± 1.2			
Hexanol	37.0 ± 1.8	38.1 ± 1.3			
Heptanol	36.7 ± 0.9	36.8 ± 1.1			
Octanol	38.0 ± 1.0	38.5 ± 0.6			
Dodecanol	36.3 ± 0.8	35.9 ± 0.8			

*Standard deviation not recorded. + Measurement made by an independent observer. † Measured 6 hours after removal from the environment.

The first two columns of Table II show that only in three environments -- methanol, butanol and aqueous sodium sulfonate solutions--is the hardness of the vitrite constituent of PSOC-293 clearly significantly different from its value in air or water. Specifically, methanol and the sodium sulfonate solutions lower the hardness by ~20% and butanol raises it by ~50%. Nor can these three results reasonably be attributed to the sort of isolated anomalies noted above because each occurs in both sections oriented perpendicular to and sections oriented parallel to the bedding plane and each has been confirmed by measurements on more than one sample. Moreover, in the cases of methanol and butanol, the confirmatory measurements were made by an independent observer who did not know the results of the first experiments.

The third and fourth columns of Table II reveal further that only methanol produces a change in microhardness lasting long enough (~1 hour) to be observed after removing the coal from overnight immersion in the test environment, and that even in this case the hardness returns to its characteristic value in air within about six hours. Finally, the last column shows that there is no further change in hardness if the specimen is subsequently repolished and re-indented in air one day later.

C. Drilling Rates

The results of the drilling rate measurements are summarized in Figure XXVI and Tables III through VIII. Figure XXVI shows the actual plots of bit penetration versus time obtained by drilling 13 holes perpendicular to the bedding plane in a single block of PSOC-248 that was relatively free of major faults and inhomogeneities, though extensively micro-cracked. The first 3 holes (curves 1-3) were drilled in water, the next 5 (curves 4-8) in HCl of (initial) pH 3.2, and the remaining 5 (curves 9-13) in NaOH of (initial) pH 9.0. It can be seen that: (i) bit penetration in all cases increases almost linearly with time, so that bit penetration rate is nearly time independent; (ii) the penetration rates obtained from successive holes drilled in the same environment are essentially identical, notwithstanding the fact that the pH (and therefore the zeta potential (see Section IIIE below)) was in each case changing continuously during the measurements; and (iii) the drilling rates obtained in different environments are the same to within the experimental scatter, which in this case is no more than $\pm 4\%$.

Tables III through VII list both the absolute drilling rates achieved in each coal in each test environment and the corresponding normalized drilling rates. And Table VIII shows the results of drilling the master block of PSOC-293 in water at periodic times during the life of the bit. The data shown in this latter table confirm straightforwardly the statement made earlier (in Section IIC) that bit wear was not a problem in this work. In contrast, the data shown in Tables III through VII reveal a somewhat less obvious picture. However, it seems clear from the many data collected in water that: (i) there is significant variation (in a few cases as much as $\pm 30\%$) in drilling rate within any one block of coal; (ii) there is in general somewhat more variation in drilling rate between different blocks of the same coal than within each such block (this is particularly true in the case of PSOC-080); and (iii) the scatter in the drilling data varies from coal to coal, with PSOC-080 showing the greatest variation and PSOC-248 and PSOC-293 the least. (It should therefore be noted that the data shown in Figure XXVI, though not atypical, were obtained from one of the two most reproducible coals studied).

Figure XXVI. Bit penetration normal to the bedding plane as a function of time for PSOC-248 in various aqueous environments.

Table III. Drilling data for PSOC-246

Specimen	Environment	Absolute Drilling Rate (10^{-3} cm/sec)	Normalized Drilling Rate
1	H ₂ O	106.5 + 4.2	1.00
2	H ₂ O	104.7 + 11.3	1.00
3	H ₂ O	87.5 + 12.9	1.00
4	H ₂ O	110.1 + 14.7	1.00
5	H ₂ O	37.6 + 8.1	1.00
1	HCl pH 3.2	103.5 + 7.6	0.97
1	HCl pH 3.7	106.2 + 7.0	1.00
2	NaOH pH 9.0	95.5 + 13.3	0.91
2	Buffer Solution pH 3.2	116.4 + 11.2	1.11
2	Buffer solution pH 3.7	104.2 + 12.6	1.00
2	Buffer solution pH 9.0	99.8 + 9.7	0.95
1	1 wt. % Na sulfonate	101.8 + 4.8	0.96
1	Methanol	103.1 + 3.3	0.97
3	Ethanol	101.1 + 9.8	1.16
3	Propanol	76.3 + 15.5	0.87
3	Butanol	74.5 + 18.3	0.85
3	Pentanol	84.8 + 20.4	0.97
4	Hexanol	89.2 + 8.7	0.81
4	Heptanol	104.0 + 8.3	0.94
4	Octanol	98.5 + 3.6	0.89
5	Dodecanol	27.4 + 4.5	0.73

Table IV. Drilling data for PSOC-248

Specimen	Environment	Absolute Drilling Rate (10^{-3} cm/sec)	Normalized Drilling Rate
1	H ₂ O	27.7 + 1.1	1.00
2	H ₂ O	32.2 ± 0.9	1.00
3	H ₂ O	31.1 ± 1.1	1.00
4	H ₂ O	28.0 ± 3.0	1.00
5	H ₂ O	30.5 ± 2.8	1.00
6	H ₂ O	31.0 ± 2.0	1.00
7	H ₂ O	33.2 ± 1.3	1.00
3	HCl pH 3.2	33.3 + 0.6	1.07
2	HCl pH 3.7	32.7 ± 0.5	1.02
3	NaOH pH 9.0	33.5 ± 1.1	1.08
1	Buffer solution pH 3.2	31.5 + 1.2	1.14
1	Buffer solution pH 3.7	30.9 ± 1.2	1.12
1	Buffer solution pH 9.0	28.9 ± 1.0	1.04
1	1 wt. % Na sulfonate	31.9 ± 1.3	1.15
1	Methanol	29.8 + 2.5	1.08
4	Ethanol	30.0 ± 1.4	1.07
4	Propanol	26.5 ± 2.4	0.95
5	Butanol	27.5 ± 2.6	0.90
5	Pentanol	24.5 ± 2.3	0.80
6	Hexanol	26.9 ± 2.1	0.87
6	Heptanol	31.2 ± 5.0	1.01
7	Octanol	33.9 ± 0.0	1.02
3	Dodecanol	15.3 ± 3.2	0.49

Table V. Drilling data for PSQC-293

Specimen	Environment	Absolute Drilling Rate (10^{-3} cm/sec)	Normalized Drilling Rate
1	H ₂ O	35.6 + 2.4	1.00
2	H ₂ O	30.7 + 6.9	1.00
3	H ₂ O	33.9 + 0.0	1.00
4	H ₂ O	35.8 + 2.1	1.00
5	H ₂ O	32.9 + 0.9	1.00
6	H ₂ O	34.1 + 3.4	1.00
7	H ₂ O	22.9 + 2.2	1.00
8	H ₂ O	31.1 + 5.4	1.00
9	H ₂ O	28.1 + 1.6	1.00
10	H ₂ O	32.5 + 1.8	1.00
11	H ₂ O	31.6 + 1.7	1.00
10	HCl pH 3.2	29.1 + 3.2	0.90
10	HCl pH 3.7	30.3 + 2.6	0.93
9	NaOH pH 9.0	29.6 + 2.0	1.05
8	Buffer solution pH 3.2	26.2 + 2.9	0.84
4	Buffer solution pH 3.7	32.1 + 2.6	0.90
3	Buffer solution pH 9.0	33.2 + 1.4	0.98
2	1 wt. % Na sulfonate	33.7 + 1.7	1.10
1	Methanol	36.6 + 1.5	1.03
4	Ethanol	38.4 + 0.5	1.07
5	Propanol	33.1 + 1.6	1.01
1	Butanol	37.5 + 1.4	1.05
5	Pentanol	29.9 + 0.9	0.91
5	Hexanol	33.0 + 0.8	1.00
6	Heptanol	34.2 + 1.7	1.00
7	Octanol	18.7 + 1.5	0.82
11	Octanol	30.7 + 2.1	0.97
8	Dodecanol	25.4 + 1.3	0.82

Table VI. Drilling data for PSOC-126

Specimen	Environment	Absolute Drilling Rate (10^{-3} cm/sec)	Normalized Drilling Rate
1	H ₂ O	54.1 + 8.3	1.00
2	H ₂ O	64.9 + 6.7	1.00
3	H ₂ O	69.8 + 17.3	1.00
4	H ₂ O	63.7 + 3.8	1.00
5	H ₂ O	59.5 + 14.9	1.00
6	H ₂ O	61.3 + 4.9	1.00
7	H ₂ O	61.6 + 0.0	1.00
4	HCl pH 3.2	61.0 + 0.0	0.96
4	HCl pH 3.7	61.0 + 0.0	0.96
3	NaOH pH 9.0	72.6 + 0.0	1.04
1	Buffer solution pH 3.2	73.8 + 22.4	1.36
2	Buffer solution pH 3.7	53.3 + 2.9	0.82
2	Buffer solution pH 9.0	60.2 + 3.8	0.93
2	1 wt. % Na Sulfonate	55.4 + 9.5	0.85
2	Methanol	72.6 + 0.0	1.12
2	Ethanol	67.9 + 7.8	1.05
2	Propanol	65.7 + 9.8	1.01
5	Butanol	58.4 + 6.8	0.98
5	Pentanol	62.7 + 12.8	1.05
5	Hexanol	58.6 + 11.0	0.98
6	Heptanol	50.8 + 10.1	0.83
6	Octanol	40.7 + 0.0	0.66
7	Dodecanol	48.4 + 3.2	0.79

Table VII. Drilling data for PSOC-080

Specimen	Environment	Absolute Drilling Rate (10^{-3} cm/sec)	Normalized Drilling Rate
1	H ₂ O	2.99 ± 0.10	1.00
2	H ₂ O	2.05 ± 0.43	1.00
3	H ₂ O	3.14 ± 0.17	1.00
4	H ₂ O	4.79 ± 0.83	1.00
5	H ₂ O	1.85 ± 0.26	1.00
6	H ₂ O	3.15 ± 1.41	1.00
6	HCl pH 3.2	2.42 ± 0.15	0.77
6	HCl pH 3.7	4.04 ± 0.93	1.28
5	NaOH pH 9.0	1.84 ± 0.36	0.99
3	Buffer solution pH 3.2	3.63 ± 0.44	1.16
3	Buffer solution pH 3.7	2.61 ± 0.38	0.83
2	Buffer solution pH 9.0	2.17 ± 0.39	1.06
3	1 wt. % Na sulfonate	3.65 ± 0.68	1.16
1	Methanol	1.94 ± 0.22	0.65
3	Ethanol	3.78 ± 0.45	1.20
4	Propanol	4.78 ± 0.68	1.00
1	Butanol	2.74 ± 0.43	0.92
4	Pentanol	4.58 ± 0.66	0.96
5	Hexanol	2.29 ± 0.64	1.24
4	Heptanol	5.94 ± 0.59	1.24
5	Octanol	1.88 ± 0.20	1.02
6	Dodecanol	0.78 ± 0.00	0.25

Table VIII. Drilling data for master block of PSOC-293 in water

Number of Holes Drilled in Other Coals in Other Environments	Absolute Drilling Rate (10 ⁻³ cm/sec)
84	32.9 ± 5.3
179	32.7 ± 1.1
304	37.6 ± 5.4
447	40.0 ± 3.5

The most important conclusion to be drawn from the drilling data reported in Tables III through VII, however, is that--with the exception of one or two anomalous results obtained in dodecanol (which environment tended to gum the drilling debris together and clog the bit)--there is no unambiguous evidence of any influence of environment on drilling rate. In particular, the three environments found to significantly affect the microhardness of vitrite--methanol, butanol and aqueous sodium sulfonate solutions--produce no corresponding effects on drilling rate either in PSOC-293 or in any of the other four coals tested.

D. Grinding Rates

(i) HGI Determinations

Table IX tabulates the results of all of the HGI determinations carried out in moist air and various liquid environments, and Figure XXVII displays graphically just those values obtained in moist air. The latter figure demonstrates something that has already been pointed out by van Krevelen⁽²⁰⁾ - namely, that in moist air the HGI varies with coal rank in the opposite sense to hardness, so that there is a rough inverse correlation between the HGI and the hardness of a coal. In addition, both the error bars in Figure XXVII and the multiple entries in Table IX demonstrate that the reproducibility of such determinations decreases with decreasing coal rank. As a result, it is difficult to obtain meaningful HGI values for lignites such as PSOC-246 without performing a large number of tests.

More importantly, however, Table IX also reveals that the HGI is affected but little by any environment, regardless of the zeta potential that environment produces (see Section IIIE). Specifically, no significant effect can be detected either in the case of PSOC-293 in any environment or in the cases of PSOC-080, -126, -248 and -246 in aqueous environments. However, the long chain alcohols do appear to have some modest effect on the HGI's of these latter coals, for the HGI increases monotonically with the molecular chain length of these environments in the case of PSOC-080 and decreases more or less regularly with the same parameter in the cases of PSOC-126, -248 and -246. In the case of PSOC-246, however, it must be reiterated that the foregoing statements are made on the basis of very poor data. Finally, it is also noted that prolonged soaking in methanol or butanol prior to testing has no effect on the HGI in these environments, at least in the cases of PSOC-126 and -293.

Figures XXVIII to XXXIII illustrate the main features of the size distribution data obtained by screening the coal ground during the HGI determinations. Thus, Figure XXVIII shows plots of the cumulative weight per cent less than size (i.e., $P_i(t)$ evaluated at $t = 180$ sec and expressed as a percentage) versus size for each of the five principal test coals ground in moist air. The particular curves shown each derive from one particular HGI determination, but the reproducibility of the data is such that only in the case of PSOC-246 are the curves derived from repeat HGI measurements distinguishable on the scale of Figure XXVIII. It is thus apparent that the size distribution curves obtained in air vary significantly and systematically with HGI. Moreover, the data derived from the four secondary coals confirm this conclusion, for the size distribution curve for St. Nicholas anthracite (HGI = 36) lies just above that for PSOC-080, the curve for Illinois No. 6 coal (HGI = 58) between those for PSOC-248 and -293 etc.

Figures XXIX to XXXIII represent an attempt to reduce to manageable proportions the vast amount of size distribution data derived from the HGI determinations carried out in different liquid environments. Each of these figures shows two curves and a series of vertical bars appropriate to one of the five principal test coals. The two curves are the cumulate w/o < size versus sieve size plots derived by averaging for each size i all of the

Environment Coal	Hardgrove Grindability Index								
	PSOC - 246	PSOC - 248	Illinois No. 6	PSOC - 293	Helena	PSOC - 126	Bethlehem Brookdale	PSOC - 080	St. Nicholas
Air	(63) 39, 63	(50) 49, 49	(57) 59	(59) 67, 69, 70	101	(122) 116, 119	105, 111	(29) 30, 34, 35	37, 35
H ₂ O	85	69		57, 63		106		34	
HCl pH 3.2	86	58		68		111		33	
HCl pH 3.7	43	51		71		118		33	
NaOH pH 9.0	86	55		70		107		34	
Buffer Solution pH 3.2	49	53		71		97		29	
Buffer Solution pH 3.7	77	52		73		100		30	
Buffer Solution pH 9.0	53	57		74		110		31	
0.1 w/o Na Sulfonate	-	54		66		96		32	
Methanol	87	53		66, 66*		115, 115*		30	
Ethanol	86	51		60		106		32	
Propanol	69	52		62, 64		100		34	
Butanol	76	43		71, 73*		97*, 101		35	
Pentanol	42	30		57, 61		93		37	
Hexanol	48	34		62		92		40	
Heptanol	46	33		69		89		45	
Octanol	52	37		57, 72, 75, 78		92		46, 48	
Dodecanol	-	-		72†		85		58	

() Values from Appendices I and II.

* Values obtained following 2 hr soaking in the test environment.

† Test conducted at temperature above room temperature.

Table IX Hardgrove grindability index as a function of environment.

Figure XXVII. Hardgrove grindability index as a function of coal rank.

Figure XXVIII. The size distributions resulting from HGI determinations on the five principal test coals in moist air environments.

Figure XXIX. Size distribution data obtained from HGI determinations on PSOC-080 in different environments.

Figure XXX. Size distribution data obtained from HGI determinations on PSOC-126 in different environments.

Figure XXXI. Size distribution data obtained from HGI determinations on PSOC-293 in different environments.

Figure XXXII. Size distribution data obtained from HGI determinations on PSOC-248 in different environments.

Figure XXXIII. Size distribution data obtained from HGI determinations on PSOC-246 in different environments.

values of w_i (180 sec) obtained from repeat measurements of the HGI in (i) moist air and (ii) distilled water environments. It will be noted that the curves labelled "air" in these figures superimpose almost exactly on the five curves derived from individual HGI determinations that are shown in Figure XXVIII, showing again the good reproducibility of the data obtained in this environment. The vertical bars represent the extreme range of values of w_i (180 sec) recorded for each size i in any HGI determination in any environment. In general, therefore, both the points representing the upper and lower ends of a given bar and those representing the same end of adjacent bars derive from different HGI determinations in different environments. Moreover, in no case do all of the upper or all of the lower end points pertain to the same environment, and in most cases such a set of points derives from three or four environments, some or all of which differ from one coal to another. Indeed, as comparison of the "air" and "water" curves shows, no clear evidence of any systematic effect of environment on grinding performance is apparent from these size distribution data. For example, in so far as it resulted in the higher value of P_i (180 sec) for any value of i (except 1), moist air appears to be a slightly more effective environment in which to grind PSOC-293 (and perhaps also PSOC-126) than does water. The same cannot be said in the case of PSOC-080, however, because this coal grinds equally effectively in both environments. And in the case of the lower rank coals, PSOC-248 and -246, P_i (180 sec) is greater for large i (small sizes) when grinding takes place in distilled water and for small i (large sizes) when the grinding environment is moist air. Furthermore, the same sort of confusion develops when attempts are made to compare grinding behavior in environments other than moist air and distilled water. This is reflected in the way in which the "air" and "water" curves vary in position relative to the vertical bars from one of Figures XXIX to XXXIII to another.

(ii) B Values

Table X and Figure XXXIV present the results of the $B_{i,1}$ determinations carried out in moist air environments on five coals of differing rank. From the former tabulation it can be seen that the absolute values of these parameters obtained by independent observers under ostensibly identical conditions agree to within about $\pm 0.01 - 0.02$, at least for PSOC-126. This is a relatively insignificant error when $i = 3$ or 4, but becomes serious when $i \geq$ (say) 7. Hence, all that legitimately can be inferred from Figure XXXIV is that $B_{i,1}$ ($i \geq 3$) generally increases slowly with increasing HGI.

The results of the corresponding studies performed on two coals in moist air, distilled water and methanol environments are displayed in Figures XXXV and XXXVI. These data reveal that, for all $i \geq 3$, water slightly increases and methanol significantly decreases $B_{i,1}$ relative to its value in air - i.e., appreciably fewer small fragments result when primary breakage occurs in methanol rather than air or water. However, the data are ambivalent as to whether soaking the coal in methanol prior to grinding enhances or reduces this effect, for soaking slightly increases $B_{i,1}$ in the case of Helena coal (Figure XXXV) and marginally decreases it in the case of the lignite PSOC-246 (Figure XXXVI).

Table X. Reproducibility of $B_{i,1}$ values for PSOC-126 in moist air environments

Sieve Number	Size (i)	$B_{i,1} \left(\begin{smallmatrix} \text{Observer} \\ A \end{smallmatrix} \right)$	$B_{i,1} \left(\begin{smallmatrix} \text{Observer} \\ B \end{smallmatrix} \right)$
16	1	1.00	1.00
20	2	1.00	1.00
30	3	0.59	0.58
50	4	0.27	0.29
70	5	0.19	0.22
100	6	0.15	0.16
140	7	0.10	0.12
200	8	0.07	0.09
270	9	0.05	0.07
400	10	0.04	0.05

Figure XXXIV. $B_{i,1}$ values as a function of coal rank in moist air environments.

Figure XXXV. $B_{i,l}$ values for Helena coal in moist air, distilled water and methanol environments.

Figure XXXVI. $B_{i,l}$ values for PSOC-246 in moist air, distilled water and methanol environments.

(iii) S Values

Only a very limited study was made of the effects of environment on the specific rate of breakage (S_1). The results are summarized in Figures XXXVII to XXXIX. In view of the paucity of the data and the considerable scatter they exhibit, however, it is probably not safe to draw from these plots any conclusions other than that S_1 increases with increasing HGI and is greater in any of the liquid environments studied (which included methanol) than in air.

E. Zeta Potentials

Figure XL shows the variation with driving pressure of the streaming potential of PSOC-293 in an aqueous HCl environment (of pH ~4), as measured in a "bleed-off" experiment during which there was no resistor connected in parallel with the plug. The two lines refer to the two directions of flow through the plug, and are marked "+" and "-" to indicate the reversal of sign accompanying reversal of flow. Because the two lines are so similar it may be inferred that the plug geometry is changing very little with reversal of flow. In addition, because both lines are straight, and because both pass close to the origin, it may also be inferred that flow through the plug is laminar in both directions and that rest potentials and polarization effects are small.

These last two conclusions are confirmed by Figure XLI, which shows actual streaming potential data obtained during 3 or 4 successive cycles of streaming methanol to and from through a plug of PSOC-293. In this case, the driving pressure was 13.0 cm of Hg (1767 kg/m²) and a resistor of 9.15 megohm was connected in parallel with the plug during the half-cycles in which the smaller peaks were recorded. The important results, however, are that the peaks are reproducible and that they follow closely the square wave form of the pressure pulses from which they derive. In particular, their short rise and fall times and their lack of any significant rounding are evidence of the absence of electrode polarization, and the near zero value of the streaming potential during the intervals when flow stops indicates that the rest potential is small.

Figure XLII shows the course of a typical streaming potential determination through the first 1800 cycles of streaming (i.e., over the first 75 hr). In this case the plug is PSOC-293 and the environment 0.1N aqueous NaCl containing sufficient HCl to reduce the initial pH to 4. It is apparent from these data that the conductivity, the streaming potential and the zeta potential all take 2-3 days to reach equilibrium values, and that the pH requires even longer. Moreover, both the streaming potential and the zeta potential have in this instance changed sign in the course of equilibration.

These long-term transient phenomena posed two problems in the present work. The first was that they severely limited the number of zeta potential determinations that could be made. And second, they suggested that very different values of zeta might develop at the solid-liquid interface during hardness, drilling rate and grinding rate studies, even when using the same coal in the same environment in all cases, for the simple reason that each of these experiments creates new surface at a very different rate. Thus, while the long-term (equilibrium) value of zeta is possibly appropriate to hardness measurements carried out on specimens prepared in the test environment over a period of many hours, it presumably is quite inappropriate to drilling or grinding studies that typically deform an element of surface milliseconds or seconds, respectively, after it is first created and exposed to the environment. Nor is this the end of the difficulties, for neither the streaming potential technique nor any other method of zeta potential determination is capable of making measurements in such short times. As a

Figure XXXVII. $w_i(t)$ versus t for St. Nicholas anthracite in various environments.

Figure XXXVIII. $w_1(t)$ versus t for PSOC-293 in various environments.

Figure XXXIX. $w_1(t)$ versus t for Bethlehem Brookdale coal in various environments.

Figure XL. Streaming potential as a function of driving pressure.

Figure XLI. Streaming potential versus time.

Figure XLII. Streaming potential, zeta potential, pH and conductivity as functions of time.

result, it was decided to concentrate on measuring the equilibrium values of zeta for PSOC-293 in simple aqueous environments and such shorter chain length alcohols as methanol and butanol (which affect its hardness, Section IIIB), and then to supplement these data with a measurement of the zeta potential of each of the other four principal test coals in just one environment in an attempt to determine the effect of coal rank on the surface chemistry of coal.

Methanol was chosen as the environment in these latter studies - partly because it affects the hardness of vitrite (which is the major constituent of all five principal test coals), and partly because it causes chemical comminution^(13,14). The results of these studies are shown in Figures XLIII to XLV.

Figure XLIII reveals that, one data point notwithstanding, the zeta potential of PSOC-293 decreases linearly with pH, passing through the isoelectric point ($\zeta = 0$) at pH ~ 5.85 . And Figure XLIV suggests that there is little effect of alcohol chain length on the zeta potential of the same coal, though the data available are so few and so scattered that this suggestion can only be regarded as very tentative. Finally, Figure XLV shows that the zeta potentials of the five principal test coals in methanol vary with their rank in somewhat the same manner as do their HGI's in this environment (and also in moist air). Again, however, the data are sparse, so this conclusion also must be regarded as tentative.

IV. CONCLUSIONS

The work described in the preceding pages has revealed two things: first, the mechanical properties of coals of any rank are much less environment-sensitive than those of inorganic rocks, minerals, ceramics and glasses; and second, such slight sensitivity as is observed apparently is not related to zeta potential. As a result, both of the questions posed in the Introduction must be answered in the negative: coal does not exhibit any obviously predictable and useful chemomechanical effects; and consequently there appears to be little prospect of reducing the cost of grinding coal through the use of chemisorption-induced changes in its near-surface flow and/or flow-dependent fracture properties.

Nevertheless, the mechanical behavior of coal is not totally environment-insensitive. Three environments - methanol, butanol and aqueous sodium sulfonate solutions - were found to affect the hardness of the (dominant) vitrite microlithotype in the high volatile bituminous A coal designated PSOC-293. Specifically, methanol and aqueous sodium sulfonate solutions lowered the hardness by $\sim 20\%$, and butanol raised it by $\sim 50\%$. However, none of these three environments-- nor any other studied - produced any effect on drilling rate large enough to detect against the background experimental scatter (up to 30% or so in some instances), except that in the cases of PSOC-248 and 080 dodecanol significantly reduced drilling performance by gumming the drilling debris together and clogging the bit. Similarly, the only effect of environment observed on overall grinding performance (as indicated by the Hardgrove Grindability Index) was a slight increase in the case of PSOC-080 in the (more viscous) longer chain alcohols and slight decreases in the cases of PSOC-126, -- 248 and (perhaps)-246 in the same environments. And this almost complete indifference to environment was also reflected in the near-sameness of the size distributions of the fines produced during these grinding studies. At first sight, therefore, it is somewhat surprising to find that the $B_{i,1}$ values obtained when grinding either PSOC-246 or Helena coal in methanol are significantly lower than those obtained when these same coals are ground in moist air. However, the observation that S_1 is in general greater in liquid environments than in air provides an explanation of this seeming inconsistency, because a methanol-induced increase in S_1 would tend to cancel out the concomitant decrease in $B_{i,1}$. Unfortunately, though, the same argument cannot be invoked in the case of water, for this environment increases both $B_{i,1}$ (albeit only slightly) and S_1 without producing any corresponding increase in grinding performance.

Figure XLIII. The equilibrium zeta potential of PSOC-293 as a function of pH.

Figure XLIV. The zeta potential of PSOC-293 in the shorter chain length n-alcohols.

Figure XLV. The zeta potentials of coals of different rank in methanol.

These results are of little practical value, but nonetheless they are interesting for a variety of reasons. First, they show that, for coal, such environmental effects as do occur exert at least as great an influence on microhardness as on drilling or grinding behavior, whereas for inorganic non-metals small changes in hardness usually translate into much larger variations in drilling and grinding performance.^(3, 21) And second, methanol, butanol and aqueous sodium sulfonate solutions have all been reported by other authors as variously affecting some aspect of the mechanical behavior of coal or of some simpler organic solid.

Thus, Polferov et al.⁽¹⁶⁾ found that a 10 percent aqueous solution of sodium sulfonate--which in the present work reduced the hardness of vitrite by approximately 20 percent--increased the grindability of anthracite fines by 20 to 30 percent. This is consistent with the chemomechanical behavior of inorganic non-metals, for which it is invariably found that drilling rate increases and grinding rate decreases as the magnitude of the zeta potential tends to zero and the hardness increases.

Likewise, it is interesting to note that butanol, which embrittles (i.e., reduces the fracture energy of) such organic materials as naphthalene⁽¹¹⁾, also raises the flow stress (i.e., the hardness) of vitrite. Phenomenologically, these results appear analogous, though they must derive from quite different mechanisms. Crystalline naphthalene presumably flows through the mechanism of dislocation glide, and therefore is embrittled by butanol because this environment either raises the near-surface flow stress by somehow making dislocation motion more difficult (as happens in the complex-ion embrittlement of ionic crystals) or somehow reduces the fracture stress at the surface (as happens in liquid metal embrittlement). Vitrite, however, is both amorphous and microscopically inhomogeneous; even at the 1 to 10 micron scale, and therefore must flow by a very different mechanism. Nonetheless, the fact that a 10 gm load produces smaller (crack-free) hardness impressions in butanol than in air shows that this (unknown) flow mechanism is somehow influenced by the environment.

In addition, the present results provide further evidence of the fact that methanol affects the mechanical behavior of coal. However, they are not entirely consistent with the previously published results⁽¹³⁾, even though these latter were obtained from Illinois No. 6 coal, a high volatile bituminous C coal not very different from PSOC-293.

Thus, on the one hand the present results show the hardness of vitrite to be the same both parallel and perpendicular to the bedding plane in all environments and to be some 20 percent lower in methanol than in water (or air). On the other hand, in his short loading time experiments (in which he used a Knoop indenter, a 200 gm load and a 30 sec loading time, and placed his indentations at random on the coal surface), Aldrich⁽¹³⁾ found the hardness parallel to the bedding plane to increase by some 8 percent and that perpendicular to the bedding plane to decrease by about 4 percent when the environment was changed from water to methanol. Aldrich also found significantly greater experimental scatter in his data--presumably as a result of his indenting both mono- and bi-maceral microlithotypes. It therefore seems reasonable to attribute the difference between the two sets of data to this latter factor rather than any other, for the change in indenter geometry would be expected to produce only quantitative and not qualitative differences in the data, and Figures XXIV and XXV suggest that neither the differences in the loading times nor the loads employed should have produced any observable change in hardness.

The drilling rate measurements made here differ from those made by Aldrich⁽¹³⁾ in using a 0.64 cm (outer) diameter diamond core bit and a load of 2600 gm rather than a 0.2 cm diameter carbide twist bit and a load ranging from 250 to 750 gm. And the present results also differ from those of Aldrich in finding no effect of methanol on drilling rate. However, it should be noted that, although Aldrich found methanol to be a more effective drilling fluid than water when using a load of 250 gm, he found the reverse to be true at 500 gm load, and there to be no influence of environment at 750 gm load. It is therefore suggested that the difference between the present results and those obtained by Aldrich is primarily a result of the fact that bit load was not varied in the present work. And it is also noted that Aldrich's observation that methanol increased the size of the drilling debris produced is consistent with the present observation of reduced $B_{i,1}$ values in this environment.

At the present time, so little is known about the detailed structure of coal, about the mechanisms by which it flows, about chemisorption and/or dissolution processes occurring at its surface, and about the penetration of liquid environments into its interior, that it is only possible to speculate about the mechanisms responsible for the effects of methanol, butanol and aqueous sodium sulfonate solutions on the hardness of vitrite. However, it is interesting to note that the first of these environments has been shown by Howard et al.⁽¹⁴⁾ to fracture coal in the absence of any externally applied mechanical stress--an effect known as chemical comminution. It may be, therefore, that it is some similar such effect--rather than any chemisorption-induced chemomechanical effect--that is responsible for the effects observed in this work. At any rate, it would seem worthwhile exploring the question of whether butanol and/or aqueous sodium sulfonate solutions also produce chemical comminution.

But this still begs the question of the detailed nature of the mechanism or mechanisms operative in this work and Aldrich's work. One possibility is that the environment weakens the coal by dissolving some species from it, either at its external surface or at the surfaces of internal cracks and pores into which it penetrates. Certainly there is evidence of dissolution in the present work--for example, the slow changes in pH that occurred during the hardness and zeta potential measurements in aqueous environments, the faster such changes that occurred in the companion drilling (and grinding) studies, and the discoloration of methanol that occurred in all experiments using this environment. Moreover, the fact that dissolution is a time-dependent process would provide a logical explanation of why a given environment might affect the hardness but not the drilling or grinding rate. But, on the other hand, the fact that the observed changes in hardness disappeared after the specimen was removed from the environment argues against a dissolution mechanism--as does the fact that butanol produces hardening rather than softening.

An alternative possibility is that the environment removes water from the coal, causing dimensional changes and fracturing as it does so, and thereby altering the mechanical behavior. But this argument also fails to explain either the disappearance of the environmental effect upon removal of the specimen from the test environment (unless it is hypothesized in addition that atmospheric moisture somehow re-enters the coal and closes the additional fractures produced by the environment) or the hardening occurring in butanol. Yet another argument suffering from the same deficiencies is that evaporation or preferential chemi- or physi-sorption of the environment in the interior of the coal promotes internal fracturing and softening.

It must therefore be concluded that there is at present no satisfactory explanation of either the present observations or Aldrich's findings available. Nor, in a material as complex as coal, will the correct explanation be easy to find. Indeed, the possibility exists that all the above processes, and perhaps also others as yet unidentified, may occur simultaneously.

V. REFERENCES

1. N. H. Macmillan, Chemisorption Induced Variations in the Plasticity and Fracture of Non-Metals, in Surface Effects in Crystal Plasticity, p. 629, Noordhoff, Leyden (1977).
2. A. R. C. Westwood and N. H. Macmillan, Environment-Sensitive Hardness of Non-Metals, in The Science of Hardness Testing and Its Research Applications, p. 377, Am. Soc. Metals, Metals Park, Ohio (1973).
3. A. R. C. Westwood, J. Mater. Sci., 9 1871 (1974).
4. N. H. Macmillan and A. R. C. Westwood, Surface Charge-Dependent Mechanical Behavior of Non-Metals, in Surfaces and Interfaces of Glass and Ceramics, p. 493, Plenum Press, New York (1974).
5. A. R. C. Westwood and R. M. Latanision, Environment-Sensitive Machining Behavior of Non-Metals, in The Science of Ceramic Machining and Surface Finishing (National Bureau of Standards Special Publication No. 348), National Bureau of Standards, Gaithersburg, Maryland (1972).
6. Handbook of Chemistry and Physics, 56th Edition, pp. E 74-80, Chemical Rubber Co. Press, Cleveland, Ohio (1975-76).
7. A. R. C. Westwood, N. H. Macmillan and R. S. Kalyoncu, J. Am. Ceram. Soc., 56 258 (1973).
8. A. R. C. Westwood, N. H. Macmillan and R. S. Kalyoncu, Trans. AIME (Mining), 256 106 (1974).
9. R. M. Gruver and H. P. Kirchner, J. Am. Ceram. Soc., 57 220 (1974).
10. P. G. Fox, Department of Metallurgy and Materials Science, University of Nottingham, England, Unpublished work (1973).
11. A. G. Skvortsov, E. A. Sinevich, N. V. Pertsov, E. D. Shchukin and P. A. Rebinder, Sov. Phys.-Doklady, 15 669 (1971).
12. A. R. C. Westwood and R. D. Huntington, Adsorption-Sensitive Flow and Fracture Behavior of Soda-Lime Glass, in Mechanical Behavior of Materials, Vol. IV, p. 383, Soc. Mater. Sci., Japan (1972).
13. R. G. Aldrich, The Effect of Chemical Additives on the Production of Fine Particles in Coal Fragmentation, Final Report on Bureau of Mines Contract No. H0101704, Syracuse University Research Corporation, Syracuse, New York, June (1971).

14. P. H. Howard (and others), Interim Reports Nos. FE-1777-1,-2, and -3 on ERDA Contract No. E(49-18)-1777, Feasibility Study of Pre-Combustion Coal Cleaning Using Chemical Comminution, Syracuse University Research Corporation, Syracuse, New York, September (1975) and January and July (1976).
15. J. A. L. Campbell, An Electrokinetic Study of Coal Froth Flotation and Flocculation, Ph.D. Thesis, The Pennsylvania State University (1969).
16. K. Y. Polferov, B. P. Kotelnikov, I. A. Roleshova, I. A. Dekin, V. E. Shevchenko, V. E. Shtefan, N. P. Deriglasov and S. G. Markin, Teploenergetika, 17 26 (1970).
- 17.. E. Stach, M.-Th. Mackowsky, M. Teichmüller, G. H. Taylor, D. Chandra and R. Teichmüller, Stach's Textbook of Coal Petrology, Gebrüder Borntraeger, Berlin and Stuttgart (1975).
18. L. F. Austin and P. T. Luckie, Powder Tech., 5 215 (1971/72).
19. D. J. Shaw, Introduction to Colloid and Surface Chemistry, 2nd Edn., Butterworths, London (1970).
20. D. W. van Krevelen, Coal, Elsevier, Amsterdam, London and New York (1961).
21. A. R. C. Westwood and J. J. Mills, Application of Chemomechanical Effects to Fracture-Dependent Industrial Processes, in Surface Effects in Crystal Plasticity, p. 835, Noordhoff, Leyden (1977).

VI. REPORTS AND PUBLICATIONS

The hardness and drilling studies described in this work formed the basis of the M.S. thesis "The Effects of Environment on the Mechanical Behavior of Coal" by O.C. Dias, which has already been accepted by The Pennsylvania State University, and the grinding studies will form parts of two other M.S. theses ("A Study of the Fine Grinding of Coals in Tumbling Ball Mills", by M. Celik, and "Chemomechanical Phenomena in the Grinding of Coal", by J. S. Shah). In addition, a brief account of this work will shortly be submitted for publication in Trans. AIME (Mining).

VII. ACKNOWLEDGEMENTS

The work described in this report was initiated under a \$10,000 grant from the Gulf Oil Foundation, P.O. Box 1166, Pittsburgh, Pennsylvania 15230

Appendix I

Characterization Data for the Five Principal Test
Coals Employed.

SAMPLE IDENTIFICATION:

PSU NUMBER -> PSOC-246
SEAM NAME -> HAGEL
ALTERNATE SEAM NAME ->
APPARENT RANK -> LIGNITE

SAMPLE HISTORY:

SAMPLING DATE & AGENCY -> 7/ 6/72 ; PSU

SAMPLE TYPE -> CHANNEL-WHOLE SEAM

ADDITIONAL INFORMATION ->

MINE INFORMATION:

RESERVES ->
ANNUAL PRODUCTION -> 1418 THOUSAND TONS

SEAM INFORMATION:

AGE OF SEAM -> PALEO.
GROUP -> FORT UNION
FORMATION ->
SEAM THICKNESS -> 7 FT. 10 IN.

SAMPLE LOCATION:

COUNTRY -> USA
STATE -> NORTH DAKOTA
COUNTY -> MERCER
TOWNSHIP ->
CITY -> STANTON

COAL PROVINCE-> NORTHERN GREAT PLAINS
REGION -> FORT UNION

MAP REFERENCE: LATITUDE -> 47 D 14 M 15 S
LONGITUDE -> 101 D 20 M 10 S
QUADRANGLE-> HANOVER, N.E. (7.5')

LIFE EXPECTANCY -> 35 YEARS

MINING METHOD -> STRIP

** PENN STATE COAL DATA BASE **

** PSOC-246 **
** 01/06/78 **
** PAGE 1 **

SAMPLE IDENTIFICATION:

PSU NUMBER -> PSOC-246
SEAM NAME -> HAGEI
ALTERNATE SEAM NAME ->
APPARENT RANK -> LIGNITE

SAMPLE LOCATION:

COUNTRY -> USA
STATE -> NORTH DAKOTA

** PENN STATE COAL DATA BASE **

** PSOC-246 **
** 01/06/78 **
** PAGE 2 **

* * * * * C H E M I C A L D A T A * * * * *

PROXIMATE ANALYSIS	AS REC'D	DRY	DAF	DMMF(PARR)
% MOISTURE	34.12			
% ASH	6.39	9.70		
% VOLATILE	29.47	44.73	49.53	49.00
% FIXED CARBON	30.02	45.57	50.47	51.00

ULTIMATE ANALYSIS	AS REC'D	DRY	DAF	DMMF(PARR)	ELEMENTAL ANALYSIS	DRY	DMMF(MOD.P)	DMMF(DIR.)
% ASH	6.39	9.70		(10.83%MM)			(10.99%MM)	(%MM)
% CARBON	42.22	64.09	70.97	71.88	% CARBON	63.67	71.52	
% HYDROGEN	2.91 (*)	4.42	4.89	4.96	% HYDROGEN	4.29	4.82	
% NITROGEN	0.92	1.40	1.55	1.57	% NITROGEN	1.40	1.57	
% TOTAL SULFUR	0.43	0.65	0.72		% ORGANIC SULFUR	0.56	0.63	
% OXYGEN(DIFF)	13.00 (*)	19.74	21.86	21.60	% OXYGEN(DIFF)	19.09	21.45	
					% MINERAL MATTER (INCL. 0.06% PES2)	10.99		

(*) -EXCLUDES MOISTURE

SULFUR FORMS	% PYRITIC	% SULFATIC	% ORGANIC	% TOTAL
DRY	0.03	0.06	0.56	0.65
DAF	0.03	0.07	0.62	0.72

DRY % CHLORINE = 0.02 DRY % CO2 = 1.55
MOTT-SPOONER DIFFERENCE = -131.

CALORIFIC VALUE (GROSS, BTU/LB)	DRY	AS REC'D MOIST.	EQUIL. MOIST.	ATOM RATIOS (DMMF)	PARR	MOD.PARR	DIRECT
MM-CONTAINING	10596.	6981.		ATOMIC H/C	0.8283	0.8099	
MM-FREE (PARR)	11847.	7494.		ATOMIC O/C	0.2256	0.2252	
MM-FREE (MOD. P)	11902.	7524.					
NET CV, DMF BTU/LB	11441.						

SAMPLE IDENTIFICATION:

PSU NUMBER -> PSOC-246
SEAM NAME -> HAGEL
ALTERNATE SEAM NAME ->
APPARENT RANK -> LIGNITE

SAMPLE LOCATION:

COUNTRY -> USA
STATE -> NORTH DAKOTA

** PENN STATE COAL DATA BASE **

** PSOC-246 **
** 01/06/78 **
** PAGE 3 **

***** RANK CALCULATIONS *****

APPARENT RANK (AS REC'D MOIST.) -> LIGNITE INTERNATIONAL RANK :
ASTH RANK (EQUIL. MOIST.) -> AS REC'D MOIST. ->
EQUIL. MOIST. ->
REFLECTANCE RANK CATEGORY -> REPORTED RANK : -> LIGNITE

***** PETROGRAPHIC DATA *****

MACERAL COMPOSITION (WHITE LIGHT ANALYSIS)

	VITRINITE	PSEUDO-VITRINITE	FUSINITE	SEMI-FUSINITE	MACRINITE	MICRINITE	SCLERO-TINITE	SPOR-INITE	RESINITE	ALGINITE	CUTINITE	
DMFP VOL. %	53.4	25.3	7.8	3.8	0.7	4.9	0.0	3.5	0.5	0.0	0.0	
DRY VOL. %	50.4	23.9	7.4	3.6	0.7	4.6	0.0	3.4	0.5	0.0	0.0	5.5 % MM
DRY WT. %	47.2	22.3	7.7	3.6	0.7	4.6	0.0	2.7	0.4	0.0	0.0	10.8 % MM

REFLECTANCE DATA

VITRINITE :
PSEUDO-VITRINITE:

HIGH: 0.51 LOW: 0.23 MEAN-MAX: 0.34
HIGH: 0.56 LOW: 0.32 MEAN-MAX: 0.45
MEAN-MAX VITRINITE + PSEUDOVITRINITE : 0.38

VITRINITE TYPES V 2 V 3 V 4 V 5
PERCENT 19.2 36.6 31.3 12.9

***** C A K I N G A N D M E C H A N I C A L P R O P E R T I E S *****

BETHLEHEM COAL PLASTOMETER:

BONDING TEMPERATURE

TEMP. MAX. FLUIDITY

SOLIDIFICATION TEMP.

FLUID TEMP. RANGE

MAXIMUM FLUIDITY

WASHABILITY DATA AVAILABLE? NO

GRAY-KING COKE TYPE

HARDGROVE GRINDABILITY 62.9

FREE SWELLING INDEX

VICKER'S HARDNESS NUMBER

SAMPLE IDENTIFICATION:

 PSU NUMBER -> PSOC-246
 SEAM NAME -> HAGEL
 ALTERNATE SEAM NAME ->
 APPARENT RANK -> LIGNITE

SAMPLE LOCATION:

 COUNTRY -> USA
 STATE -> NORTH DAKOTA

** PENN STATE COAL DATA BASE **

** PSOC-246 **
 ** 01/06/78 **
 ** PAGE 4 **

SURFACE AREA AND DENSITY DATA (ALL DATA ON 40 X 70 MESH COAL)

 SURFACE AREAS (SQ. M/G, MM-FREE) NITROGEN (77 DEG K) : 1.9 CARBON DIOXIDE (298 DEG K) : 227.

SAMPLE IDENTIFICATION:

PSU NUMBER -> PSOC-248
SEAM NAME -> ADAVILLE #1
ALTERNATE SEAM NAME ->
APPARENT RANK ->

SAMPLE HISTORY:

SAMPLING DATE & AGENCY -> 7/12/72 ; PSU

SAMPLE TYPE -> CHANNEL-WHOLE SEAM

ADDITIONAL INFORMATION ->

MINE INFORMATION:

RESERVES ->
ANNUAL PRODUCTION -> 1844 THOUSAND TONS

SAMPLE LOCATION:

COUNTRY -> USA
STATE -> WYOMING
COUNTY -> LINCOLN
TOWNSHIP ->
CITY -> KEMMERER

COAL PROVINCE-> ROCKY MOUNTAIN
REGION -> HAMS FORK

MAP REFERENCE: LATITUDE -> 41 D 47 N 0 S
LONGITUDE -> 110 D 33 W 0 S
QUADRANGLE-> KEMMERER (15')

LIFE EXPECTANCY -> 50 YEARS

MINING METHOD -> STRIP

** PENN STATE COAL DATA BASE **

** PSOC-248 **
** 01/06/78 **
** PAGE 1 **

SEAM INFORMATION:

AGE OF SEAM -> CRET.
GROUP -> MESA VERDE
FORMATION -> ADAVILLE
SEAM THICKNESS -> 100 FT. 0 IN.

SAMPLE IDENTIFICATION:

PSU NUMBER -> PSOC-248
SEAM NAME -> ADAVILLE #1
ALTERNATE SEAM NAME ->
APPARENT RANK ->

SAMPLE LOCATION:

COUNTRY -> USA
STATE -> WYOMING

** PENN. STATE COAL DATA BASE **

** PSOC-248 **
** 01/06/78 **
** PAGE 2 **

***** CHEMICAL DATA *****

PROXIMATE ANALYSIS	AS REC'D	DRY	DAF	DMHF(PARR)
% MOISTURE	19.17			
% ASH	2.37	2.93		
% VOLATILE	35.16	43.50	44.81	44.58
% FIXED CARBON	43.30	53.57	55.19	55.42

ULTIMATE ANALYSIS	AS REC'D	DRY	DAF	DMHF(PARR)	ELEMENTAL ANALYSIS	DRY	DMHF(MOD. P)	DMHF(DIR.)
% ASH	2.37	2.93		(3.52%MM)			(3.34%MM)	(%MM)
% CARBON	58.97	72.96	75.16	75.62	% CARBON	72.92	75.44	
% HYDROGEN	4.04 (*)	5.00	5.15	5.18	% HYDROGEN	4.96	5.13	
% NITROGEN	1.36	1.68	1.73	1.74	% NITROGEN	1.68	1.74	
% TOTAL SULFUR	0.52	0.64	0.66		% ORGANIC SULFUR	0.61	0.63	
% OXYGEN (DIFF)	13.57 (*)	16.79	17.30	17.46	% OXYGEN (DIFF)	16.48	17.06	
					% MINERAL MATTER (INCL. 0.06% PES2)	3.34		

(*) - EXCLUDES MOISTURE

SULFUR FORMS	% PYRITIC	% SULFATIC	% ORGANIC	% TOTAL
DRY	0.03	0.0	0.61	0.64
DAF	0.03	0.0	0.63	0.66

DRY % CHLORINE = 0.04 DRY % CO2 =
MOTT-SPOONER DIFFERENCE = 72.

CALORIFIC VALUE (GROSS, BTU/LB)	DRY	AS REC'D MOIST.	EQUIL. MOIST.	ATOM RATIOS (DMHF)	PARR	MOD. PARR	DIRECT
MM-CONTAINING	12661.	10234.		ATOMIC H/C	0.8231	0.8172	
MM-FREE (PARR)	13089.	10507.		ATOMIC O/C	0.1733	0.1697	
MM-FREE (MOD. P)	13097.	10517.					
NET CV, DMHF BTU/LB	12618.						

SAMPLE IDENTIFICATION:

 PSU NUMBER -> PSOC-248
 SEAM NAME -> ADAVILLE #1
 ALTERNATE SEAM NAME ->
 APPARENT RANK ->

SAMPLE LOCATION:

 COUNTRY -> USA
 STATE -> WYOMING

** PENN STATE COAL DATA BASE **

** PSOC-248 **
 ** 01/06/78 **
 ** PAGE 3 **

***** RANK CALCULATIONS *****

APPARENT RANK (AS REC'D MOIST.) -> INTERNATIONAL RANK :
 AS REC'D MOIST. ->
 ASTM RANK (EQUIL. MOIST.) -> EQUIL. MOIST. ->
 REFLECTANCE RANK CATEGORY -> HVC REPORTED RANK : ->

***** PETROGRAPHIC DATA *****

MACERAL COMPOSITION (WHITE LIGHT ANALYSIS)

	VITRINITE	PSEUDO-VITRINITE	FUSINITE	SEMI-FUSINITE	MACRINITE	MICRINITE	SCLERO-TINITE	SPORINITE	RESINITE	ALGINITE	CUTINITE	
DMMP VOL. %	68.2	8.1	0.7	11.8	0.0	9.5	0.1	1.2	0.4	0.0	0.0	
DRY VOL. %	67.0	8.0	0.7	11.6	0.0	9.3	0.1	1.2	0.4	0.0	0.0	1.7 % HM 00

REFLECTANCE DATA

VITRINITE :
 PSEUDO-VITRINITE:

HIGH: 0.56 LOW: 0.41 MEAN-MAX: 0.47
 HIGH: 0.59 LOW: 0.44 MEAN-MAX: 0.51
 MEAN-MAX VITRINITE + PSEUDOVITRINITE : 0.47

VITRINITE TYPES V 4 V 5

 PERCENT 68.4 31.6

***** CAKING AND MECHANICAL PROPERTIES *****

BETHLEHEM COAL PLASTOMETER:

BONDING TEMPERATURE

TEMP. MAX. FLUIDITY

SOLIDIFICATION TEMP.

FLUID TEMP. RANGE

MAXIMUM FLUIDITY

WASHABILITY DATA AVAILABLE? NO

GRAY-KING COKE TYPE

HARDGROVE GRINDABILITY 49.7

FREE SWELLING INDEX

VICKER'S HARDNESS NUMBER 22.6

SAMPLE IDENTIFICATION:

 PSU NUMBER -> PSOC-248
 SEAM NAME -> ADAVILLE #1
 ALTERNATE SEAM NAME ->
 APPARENT RANK ->

SAMPLE LOCATION:

 COUNTRY -> USA
 STATE -> WYOMING

** PENN STATE COAL DATA BASE **

**
 ** PSOC-248 **
 **
 ** 01/06/78 **
 ** PAGE 4 **

SURFACE AREA AND DENSITY DATA (ALL DATA ON 40 X 70 MESH COAL)

 SURFACE AREAS (SQ. M/G, MM-FREE) NITROGEN (77 DEG K) : 15.0 CARBON DIOXIDE (298 DEG K) : 193.

SAMPLE IDENTIFICATION:

PSU NUMBER -> PSOC-293
SEAM NAME -> PITTSBURGH
ALTERNATE SEAM NAME ->
APPARENT RANK -> HVA

SAMPLE HISTORY:

SAMPLING DATE & AGENCY -> 12/ 4/73 ; PSU

SAMPLE TYPE -> CHANNEL-BENCH

ADDITIONAL INFORMATION -> SEE LITHOTYPE: PSOC-295

MINE INFORMATION:

RESERVES ->

ANNUAL PRODUCTION -> 2205 THOUSAND TONS

SAMPLE LOCATION:

COUNTRY -> USA

STATE -> PENNSYLVANIA

COUNTY -> WASHINGTON

TOWNSHIP ->

CITY -> THOMAS

COAL PROVINCE-> EASTERN

REGION -> APPALACHIAN

MAP REFERENCE: LATITUDE -> 40 D 14 M 0 S

LONGITUDE -> 80 D 6 M 0 S

QUADRANGLE-> HACKETT (7.5')

LIFE EXPECTANCY -> 43 YEARS

MINING METHOD -> UNDERGROUND

** PENN STATE COAL DATA BASE **

** **

** PSOC-293 **

** **

** 01/06/78 **

** PAGE 1 **

SEAM INFORMATION:

AGE OF SEAM -> PENNSYL.

GROUP -> MONONGAHELA

FORMATION ->

SEAM THICKNESS -> 6 FT. 11 IN.

** SEAM PROFILE **

ROOF -> SHALE

8 IN. -> ROOF COAL (294)

10 IN. -> SLATE, SHALE--N/S

55 IN. -> COAL **

10 IN. -> COAL (295) **

FLOOR ->

SAMPLE IDENTIFICATION:

PSU NUMBER -> PSOC-293
SEAM NAME -> PITTSBURGH
ALTERNATE SEAM NAME ->
APPARENT RANK -> HVA

SAMPLE LOCATION:

COUNTRY -> USA
STATE -> PENNSYLVANIA

** PENN STATE COAL DATA BASE **

**
** PSOC-293 **
**
** 01/06/78 **
** PAGE 2 **

* * * * * C H E M I C A L D A T A * * * * *

PROXIMATE ANALYSIS	AS REC'D	DRY	DAF	DMMP(PARR)	
% MOISTURE	1.82				% EQUILIBRIUM MOISTURE = 3.92
% ASH	8.54	8.70			MM-FREE = 4.35
% VOLATILE	36.11	36.78	40.28	39.43	
% FIXED CARBON	53.53	54.52	59.72	60.57	

ULTIMATE ANALYSIS	AS REC'D	DRY	DAF	DMMP(PARR)	ELEMENTAL ANALYSIS	DRY	DMMP(MOD.PL)	DMMP(DIR.1)
% ASH	8.54	8.70		(10.47%MM)			(10.48%MM)	(10.35%MM)
% CARBON	76.58	78.00	85.43	87.12	% CARBON	77.87	86.99	86.86
% HYDROGEN	4.62 (*)	4.71	5.16	5.26	% HYDROGEN	4.57	5.11	5.10
% NITROGEN	2.02	2.06	2.26	2.30	% NITROGEN	2.06	2.30	2.30
% TOTAL SULFUR	1.91	1.95	2.14		% ORGANIC SULFUR	0.65	0.73	0.73
% OXYGEN (DIFF)	4.50 (*)	4.58	5.02	5.32	% OXYGEN (DIFF)	4.50	4.88	5.02
(*) -EXCLUDES MOISTURE					% MINERAL MATTER	10.35		
					(INCL. 2.41% PES2)			

SULFUR FORMS	% PYRITIC	% SULFATIC	% ORGANIC	% TOTAL	
DRY	1.29	0.01	0.65	1.95	DRY % CHLORINE = 0.09 DRY % CO2 =
DAF	1.41	0.01	0.71	2.14	MOTT-SPOONER DIFFERENCE = -127.

CALORIFIC VALUE (GROSS, BTU/LB)	DRY	AS REC'D MOIST.	EQUIL. MOIST.	ATOM RATIOS (DMMP)	PARR	MOD.PARR	DIRECT
MM-CONTAINING	13743.	13493.	13204.	ATOMIC H/C	0.7253	0.7051	0.7051
MM-FREE (PARR)	15241.	14932.	14577.	ATOMIC O/C	0.0458	0.0421	0.0434
MM-FREE (DIRECT)	15252.	14943.	14588.				
NET CV, DMMP BTU/LB	14765.						

SAMPLE IDENTIFICATION:

PSU NUMBER -> PSOC-293
SEAM NAME -> PITTSBURGH
ALTERNATE SEAM NAME ->
APPARENT RANK -> HVA

SAMPLE LOCATION:

COUNTRY -> USA
STATE -> PENNSYLVANIA

** PENN STATE COAL DATA BASE **

** PSOC-293 **
** 01/06/78 **
** PAGE 3 **

***** RANK CALCULATIONS *****

APPARENT RANK (AS REC'D MOIST.) -> HVA INTERNATIONAL RANK :
ASTM RANK (EQUIL. MOIST.) -> HVA AS REC'D MOIST. -> 634
REFLECTANCE RANK CATEGORY -> HVA EQUIL. MOIST. -> 634
REPORTED RANK : ->

***** PETROGRAPHIC DATA *****

MACERAL COMPOSITION (WHITE LIGHT ANALYSIS)

	VITRINITE	PSEUDO-VITRINITE	FUSINITE	SEMI-FUSINITE	MACRINITE	MICRINITE	SCLERO-TINITE	SPOR-INITE	RESINITE	ALGINITE	CUTINITE	
DMMF VOL. %	73.1	7.1	4.8	2.6	1.9	6.0	0.0	4.2	0.3	0.0	0.0	
DRY VOL. %	69.2	6.7	4.5	2.5	1.8	5.7	0.0	4.0	0.3	0.0	0.0	5.3 % MM
DRY WT. %	64.6	6.3	4.9	2.5	1.8	5.7	0.0	3.5	0.2	0.0	0.0	10.5 % MM

REFLECTANCE DATA

VITRINITE :

PSEUDO-VITRINITE:

HIGH: 0.89 LOW: 0.71 MEAN-MAX: 0.81
HIGH: 0.99 LOW: 0.88 MEAN-MAX: 0.93
MEAN-MAX VITRINITE + PSEUDOVITRINITE : 0.82

VITRINITE TYPES

	V 7	V 8	V 9
PERCENT	28.3	63.3	8.3

***** C A K I N G A N D M E C H A N I C A L P R O P E R T I E S *****

GIESELER COAL PLASTOMETER:

INIT. SOFTENING TEMP 397
TEMP. MAX. FLUIDITY 449
SOLIDIFICATION TEMP. 475
FLUID TEMP. RANGE 78
MAXIMUM FLUIDITY 4900

GRAY-KING COKE TYPE G7
HARDGROVE GRINDABILITY 59.4
FREE SWELLING INDEX 8.5
VICKER'S HARDNESS NUMBER 37.9

WASHABILITY DATA AVAILABLE? NO

SAMPLE IDENTIFICATION:

 PSU NUMBER -> PSOC-126
 SEAM NAME -> LOWER KITTANNING
 ALTERNATE SEAM NAME -> PENNSYLVANIA B
 APPARENT RANK -> LOW VOL

SAMPLE HISTORY:

 SAMPLING DATE & AGENCY -> 5/22/68 ; PSU

SAMPLE TYPE -> CHANNEL-WHOLE SEAM
 ADDITIONAL INFORMATION -> SEE LITHOTYPES: PSOC-127, 128, 129

MINE INFORMATION:

 RESERVES ->
 ANNUAL PRODUCTION -> 1431 THOUSAND TONS

SAMPLE LOCATION:

 COUNTRY -> USA
 STATE -> PENNSYLVANIA
 COUNTY -> CAMBRIA
 TOWNSHIP ->
 CITY -> EBENSBURG
 COAL PROVINCE-> EASTERN
 REGION -> APPALACHIAN

MAP REFERENCE: LATITUDE -> 40 D. 27 M 30 S
 LONGITUDE -> 78 D 42 M 0 S
 QUADRANGLE-> EBENSBURG (7.5')

** PENN STATE COAL DATA BASE **

 ** PSOC-126 **
 ** 01/06/78 **
 ** PAGE 1 **

SEAM INFORMATION:

 AGE OF SEAM -> PENNSYL.
 GROUP -> ALLEGHENY
 FORMATION ->
 SEAM THICKNESS -> 4 FT. 1 IN.

** SEAM PROFILE **

ROOF -> DARK GRAY SHALE
 11 IN. -> TOUGH, BONEY (128)
 4 IN. -> VERY BRIGHT (129)
 1 IN. -> DURAIN
 24 IN. -> BRIGHT
 0 IN. -> BONEY PARTING
 9 IN. -> BRIGHT (127)
 FLOOR -> SANDSTONE

SAMPLE IDENTIFICATION:

PSU NUMBER -> PSOC-126
SEAM NAME -> LOWER KITTANNING
ALTERNATE SEAM NAME -> PENNSYLVANIA B
APPARENT RANK -> LOW VOL

SAMPLE LOCATION:

COUNTRY -> USA
STATE -> PENNSYLVANIA

** PENN STATE COAL DATA BASE **

** PSOC-126 **
** 01/06/78 **
** PAGE 2 **

***** CHEMICAL DATA *****

PROXIMATE ANALYSIS	AS REC'D	DRY	DAF	DMMP(PARR)
% MOISTURE	0.64			
% ASH	6.97	7.01		
% VOLATILE	18.50	18.62	20.02	19.19
% FIXED CARBON	73.89	74.37	79.98	80.81

ULTIMATE ANALYSIS	AS REC'D	DRY	DAF	DMMP(PARR)	ELEMENTAL ANALYSIS	DRY	DMMP(MOD.P)	DMMP(DIR.)
% ASH	6.97	7.01		(8.17%MM)			(8.24%MM)	(%MM)
% CARBON	82.37	82.90	89.15	90.28	% CARBON	82.80	90.23	
% HYDROGEN	4.43 (*)	4.46	4.80	4.86	% HYDROGEN	4.36	4.75	
% NITROGEN	0.85	0.86	0.92	0.94	% NITROGEN	0.86	0.94	
% TOTAL SULFUR	1.08	1.09	1.17		% ORGANIC SULFUR	0.44	0.48	
% OXYGEN(DIFF)	3.66 (*)	3.68	3.96	3.93	% OXYGEN(DIFF)	3.31	3.60	

(*) -EXCLUDES MOISTURE

% MINERAL MATTER 8.24
(INCL. 1.18% FES2)

SULFUR FORMS	% PYRITIC	% SULFATIC	% ORGANIC	% TOTAL
DRY	0.63	0.02	0.44	1.09
DAF	0.68	0.02	0.47	1.17

DRY % CHLORINE = 0.04 DRY % CO2 =
MOTT-SPOONER DIFFERENCE = 147.

CALORIFIC VALUE (GROSS, BTU/LB)	DRY	AS REC'D MOIST.	EQUIL. MOIST.	ATOM RATIOS (DMMP)	PARR	MOD.PARR	DIRECT
MM-CONTAINING	14603.	14510.		ATOMIC H/C	0.6462	0.6319	
MM-FREE (PARR)	15843.	15733.		ATOMIC O/C	0.0327	0.0300	
MM-FREE (MOD. P)	15877.	15766.					
NET CV, DMMP BTU/LB	15426.						

SAMPLE IDENTIFICATION:

PSU NUMBER -> PSOC-126
SEAM NAME -> LOWER KITTANNING
ALTERNATE SEAM NAME -> PENNSYLVANIA B
APPARENT RANK -> LOW VOL

SAMPLE LOCATION:

COUNTRY -> USA
STATE -> PENNSYLVANIA

** PENN STATE COAL DATA BASE **

** PSOC-126 **
** C1/06/78 **
** PAGE 3 **

***** RANK CALCULATIONS *****

APPARENT RANK (AS REC'D MOIST.) -> LOW VOL INTERNATIONAL RANK :
ASTM RANK (EQUIL. MOIST.) -> AS REC'D MOIST. ->
REFLECTANCE RANK CATEGORY -> LOW VOL REPORTED RANK : ->
EQUIL. MOIST. ->

***** PETROGRAPHIC DATA *****

MACERAL COMPOSITION (WHITE LIGHT ANALYSIS)

	VITRINITE	PSEUDO-VITRINITE	FUSINITE	SEMI-FUSINITE	MACRINITE	MICRINITE	SCLERO-TINITE	SPOR-INITE	RESINITE	ALGINITE	CUTINITE	
DMFP VOL. %	86.0	0.0	2.3	1.8	1.8	8.1	0.0	0.0	0.0	0.0	0.0	
DRY VOL. %	82.5	0.0	2.2	1.7	1.7	7.8	0.0	0.0	0.0	0.0	0.0	4.1 % MM
DRY WT. %	78.3	0.0	2.4	1.7	1.7	7.8	0.0	0.0	0.0	0.0	0.0	8.2 % MM

REFLECTANCE DATA VITRINITE : HIGH: 1.77 LOW: 1.57 MEAN-MAX: 1.68

VITRINITE TYPES V15 V16 V17
PERCENT 4.0 59.0 37.0

***** C A K I N G A N D M E C H A N I C A L P R O P E R T I E S *****

BETHLEHEM COAL PLASTOMETER:

BONDING TEMPERATURE
TEMP. MAX. FLUIDITY
SOLIDIFICATION TEMP.
FLUID TEMP. RANGE
MAXIMUM FLUIDITY

GRAY-KING COKE TYPE

HARDGROVE GRINDABILITY 122.5
FREE SWELLING INDEX
VICKER'S HARDNESS NUMBER 24.3

WASHABILITY DATA AVAILABLE? YES ; NUMBER OF FRACTIONS: 33

SAMPLE IDENTIFICATION:

PSU NUMBER -> PSOC-126
SEAM NAME -> LOWER KITTTANNING
ALTERNATE SEAM NAME -> PENNSYLVANIA B
APPARENT RANK -> LOW VOL

SAMPLE LOCATION:

COUNTRY -> USA
STATE -> PENNSYLVANIA

** PENN STATE COAL DATA BASE **

** PSOC-126 **
** 01/06/78 **
** PAGE 4 **

MAJOR ELEMENT ANALYSIS

% HTA = 6.90

	SI02	AL2O3	TIO2	FE2O3	MGO	CAO	NA2O	K2O	P2O5	SO3
OXIDE % OF HTA	45.7	37.1	1.21	11.8	0.27	1.56	0.30	0.86	0.17	
ELEMENT % OF TOTAL DRY COAL	SI	AL	TI	FE	MG	CA	NA	K	P	S
	1.5	1.4	0.05	0.6	0.01	0.08	0.02	0.05	0.01	1.09

TRACE ELEMENT ANALYSIS

% HTA = 6.90

	PPM HTA	PPM TOTAL COAL		PPM HTA	PPM TOTAL COAL		PPM HTA	PPM TOTAL COAL	VOLATILES -----	PPM TOTAL COAL
AG	< 1.0	< 0.1	GE	< 25.	< 2.	SN	34.	2.	AS	
B			LA	74.	5.	SR	603.	42.	BR	
BA	192.	13.	LI			TH			CD	
BE	19.	1.	MN	31.	2.	U	7.3	0.5	CL	400.
BI	< 20.	< 1.	MO			V	206.	14.	F	
CE	170.	12.	NB	< 20.	< 1.	Y	76.	5.	HG	0.16
CO	70.	5.	NI	90.	6.	YB	12.	1.	SB	
CR	210.	14.	PB	150.	10.	ZN	217.	15.	SE	
CU	128.	9.	RB	39.	3.	ZR	229.	16.		
GA	56.	4.	SC	34.	2.					

SAMPLE IDENTIFICATION:

PSU NUMBER -> PSOC-080
SEAM NAME -> BUCK MOUNTAIN
ALTERNATE SEAM NAME ->
APPARENT RANK -> AN

SAMPLE HISTORY:

SAMPLING DATE & AGENCY -> 9/27/67 ; PSU

SAMPLE TYPE -> CHANNEL-WHOLE SEAM
ADDITIONAL INFORMATION -> SEE LITHOTYPES: PSOC-81, 82

MINE INFORMATION:

RESERVES ->
ANNUAL PRODUCTION ->

SAMPLE LOCATION:

COUNTRY -> USA
STATE -> PENNSYLVANIA
COUNTY -> SCHUYKILL
TOWNSHIP ->
CITY -> ZERBE
COAL PROVINCE -> EASTERN
REGION -> ANTHRACITE

MAP REFERENCE: LATITUDE -> 40 D 39 M 30 S
LONGITUDE -> 76 D 21 M 0 S
QUADRANGLE -> MINERSVILLE (7.5')

** PENN STATE COAL DATA BASE **

** PSOC-080 **
** 01/06/78 **
** PAGE 1 **

LIFE EXPECTANCY ->
MINING METHOD ->

SEAM INFORMATION:

AGE OF SEAM -> PENNSYL.
GROUP ->
FORMATION -> LLEWELLYN
SEAM THICKNESS -> 4 FT. 0 IN.

** SEAM PROFILE **

ROOF -> CONGLOMERATE
7 IN. -> BRIGHT
12 IN. -> BRIGHT, FRIABLE (81)
3 IN. -> BONY PARTING
9 IN. -> BRIGHT
8 IN. -> DULL, BLOCKY (82)
9 IN. -> BRIGHT
FLOOR -> CONGLOMERATE

SAMPLE IDENTIFICATION:

PSU NUMBER -> PSOC-080
 SEAM NAME -> BUCK MOUNTAIN
 ALTERNATE SEAM NAME ->
 APPARENT RANK -> AN

SAMPLE LOCATION:

COUNTRY -> USA
 STATE -> PENNSYLVANIA

** PENN STATE COAL DATA BASE **

**
 ** PSOC-080 **
 **
 ** 01/06/78 **
 ** PAGE 2 **

* * * * * C H E M I C A L D A T A * * * * *

PROXIMATE ANALYSIS	AS REC'D	DRY	DAF	DMMP(PARR)
% MOISTURE	2.51			
% ASH	13.59	13.94		
% VOLATILE	5.63	5.77	6.70	5.24
% FIXED CARBON	78.27	80.29	93.30	94.76

ULTIMATE ANALYSIS	AS REC'D	DRY	DAF	DMMP(PARR)	ELEMENTAL ANALYSIS	DRY	DMMP(MOD.P)	DMMP(DIR.)
% ASH	13.59	13.94		(15.36%MM)			(15.76%MM)	(15.36%MM)
% CARBON	76.22	78.18	90.84	92.37	% CARBON	78.12	92.74	92.30
% HYDROGEN	2.19 (*)	2.25	2.61	2.66	% HYDROGEN	2.06	2.45	2.43
% NITROGEN	0.64	0.66	0.77	0.78	% NITROGEN	0.66	0.78	0.78
% TOTAL SULFUR	0.54	0.55	0.64		% ORGANIC SULFUR	0.53	0.63	0.63
% OXYGEN(DIFF)	4.31 (*)	4.42	5.14	4.20	% OXYGEN(DIFF)	3.27	3.41	3.86

(*) -EXCLUDES MOISTURE

% MINERAL MATTER 15.36
 (INCL. 0.04% PES2)

SULFUR FORMS	% PYRITIC	% SULFATIC	% ORGANIC	% TOTAL
DRY	0.02	0.0	0.53	0.55
DAF	0.02	0.0	0.62	0.64

DRY % CHLORINE = 0.0 DRY % CO2 = 0.22

MOTT-SPOONER DIFFERENCE = 283.

CALORIFIC VALUE (GROSS, BTU/LB)	DRY	AS REC'D MOIST.	EQUIL. MOIST.
MM-CONTAINING	12603.	12287.	
MM-FREE (PARR)	14857.	14419.	
MM-FREE (DIRECT)	14889.	14449.	
NET CV, DMMP BTU/LB	14642.		

ATOM RATIOS (DMMP)	PARR	MOD.PARR	DIRECT
ATOMIC H/C	0.3457	0.3167	0.3167
ATOMIC O/C	0.0341	0.0276	0.0314

SAMPLE IDENTIFICATION:

PSU NUMBER -> PSOC-080
SEAM NAME -> BUCK MOUNTAIN
ALTERNATE SEAM NAME ->
APPARENT RANK -> AN

SAMPLE LOCATION:

COUNTRY -> USA
STATE -> PENNSYLVANIA

** PENN STATE COAL DATA BASE **

** PSOC-080 **
** 01/06/78 **
** PAGE 3 **

***** RANK CALCULATIONS *****

APPARENT RANK (AS REC'D MOIST.) -> AN INTERNATIONAL RANK :
ASTM RANK (EQUIL. MOIST.) -> AS REC'D MOIST. ->
REFLECTANCE RANK CATEGORY -> AN EQUIL. MOIST. ->
REPORTED RANK : -> AN

***** PETROGRAPHIC DATA *****

MACERAL COMPOSITION (WHITE LIGHT ANALYSIS)

	VITRINITE	PSEUDO-VITRINITE	FUSINITE	SEMI-FUSINITE	MACRINITE	MICRINITE	SCLERO-TINITE	SPOR-INITE	RESINITE	ALGINITE	CUTINITE	
DMMP VOL. %	96.3	0.0	2.0	1.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
DRY VOL. %	88.6	0.0	1.8	1.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	8.0 % MM
DRY WT. %	81.3	0.0	1.9	1.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	15.4 % MM

REFLECTANCE DATA VITRINITE : HIGH: 4.96 LOW: 2.50 MEAN-MAX: 4.17

***** NUMBER OF V-TYPES IS GREATER THAN 10; CONSULT ORIGINAL DATA FOR INFORMATION *****

***** C A K I N G A N D M E C H A N I C A L P R O P E R T I E S *****

BETHLEHEM COAL PLASTOMETER:

BONDING TEMPERATURE
TEMP. MAX. FLUIDITY
SOLIDIFICATION TEMP.
FLUID TEMP. RANGE
MAXIMUM FLUIDITY

GRAY-KING COKE TYPE

HARDGROVE GRINDABILITY 28.9
FREE SWELLING INDEX
VICKER'S HARDNESS NUMBER

WASHABILITY DATA AVAILABLE? NO

SAMPLE IDENTIFICATION:

PSU NUMBER -> PSOC-080
SEAM NAME -> BUCK MOUNTAIN
ALTERNATE SEAM NAME ->
APPARENT RANK -> AN

SAMPLE LOCATION:

COUNTRY -> USA
STATE -> PENNSYLVANIA

** PENN STATE COAL DATA BASE **

** PSOC-080 **
** 01/06/78 **
** PAGE 4 **

MAJOR ELEMENT ANALYSIS

% HTA = 7.93

	SIO2	AL2O3	TIO2	FE2O3	MGO	CAO	NA2O	K2O	P2O5	SO3
OXIDE % OF HTA	54.9	32.4	3.82	3.29	1.09	1.53	0.12	1.22	0.06	2.10
ELEMENT % OF	SI	AL	TI	FE	MG	CA	NA	K	P	S
TOTAL DRY COAL	2.0	1.4	0.18	0.18	0.05	0.09	0.01	0.08	0.002	0.55

TRACE ELEMENT ANALYSIS

% HTA = 7.93

	PPM HTA	PPM TOTAL COAL		PPM HTA	PPM TOTAL COAL		PPM HTA	PPM TOTAL COAL	VOLATILES -----	PPM TOTAL COAL
AG	< 1.0	< 0.1	GE	< 25.	< 2.	SN	200.	16.	AS	
B			LA	150.	12.	SR	220.	17.	BR	
BA	1700.	135.	LI			TH			CD	
BE	7.8	0.6	MN	170.	13.	U	15.	1.	CL	<100.
BI	< 20.	< 2.	MO			V	300.	24.	F	
CE	130.	10.	NB	< 20.	< 2.	Y	70.	6.	HG	0.05
CO	420.	33.	NI	1600.	127.	YB	9.0	0.7	SB	
CR	560.	44.	PB	140.	11.	ZN	57.	5.	SE	
CU	260.	21.	RB	10.	1.	ZR	160.	13.		
GA	76.	6.	SC	54.	4.					

SAMPLE IDENTIFICATION:

 PSU NUMBER -> PSOC-080
 SEAM NAME -> BUCK MOUNTAIN
 ALTERNATE SEAM NAME ->
 APPARENT RANK -> AN

SAMPLE LOCATION:

 COUNTRY -> USA
 STATE -> PENNSYLVANIA

** PENN STATE COAL DATA BASE **

** PSOC-080 **
 ** 01/06/78 **
 ** PAGE 5 **

SURFACE AREA AND DENSITY DATA (ALL DATA ON 40 X 70 MESH COAL)

 SURFACE AREAS (SQ. M/G, MM-FREE) NITROGEN (77 DEG K) : 8.3 CARBON DIOXIDE (298 DEG K) : 484.
 DENSITY DATA (G/CC, MM-FREE) HELIUM : 1.53 MERCURY : 1.37 OPEN PORE VOLUME (CC/G) : 0.076

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Appendix II

Characterization Data for Illinois No. 6 Coal

SAMPLE IDENTIFICATION:

PSU NUMBER -> PSOC-022
SEAM NAME -> ILLINOIS #6
ALTERNATE SEAM NAME ->
APPARENT RANK ->

SAMPLE HISTORY:

SAMPLING DATE & AGENCY -> 5/23/67 ; PSU

SAMPLE TYPE -> CHANNEL-WHOLE SEAM

ADDITIONAL INFORMATION ->

MINE INFORMATION:

RESERVES ->

ANNUAL PRODUCTION -> 1519 THOUSAND TONS

SAMPLE LOCATION:

COUNTRY -> USA
STATE -> ILLINOIS
COUNTY -> KNOX
TOWNSHIP ->
CITY -> VICTORIA
COAL PROVINCE-> INTERIOR
REGION -> EASTERN

MAP REFERENCE: LATITUDE -> 41 D 1 M 0 S
LONGITUDE -> 90 D 5 M 50 S
QUADRANGLE-> GALVA (15')

LIFE EXPECTANCY ->

MINING METHOD -> STRIP

** PENN STATE COAL DATA BASE **

**
** PSOC-022 **
**
** 01/06/78 **
** PAGE 1 **

SEAM INFORMATION:

AGE OF SEAM -> PENNSYL.

GROUP -> KEWANEE

FORMATION -> CARBONDALE

SEAM THICKNESS -> 4 FT. 0 IN.

** SEAM PROFILE **

ROOF -> BLACK, SLATY SHALE

33 IN. -> COAL

3 IN. -> CLAY PARTING

12 IN. -> COAL

FLOOR -> FINE CLAY

SAMPLE IDENTIFICATION:

PSU NUMBER -> PSOC-022
SEAM NAME -> ILLINOIS #6
ALTERNATE SEAM NAME ->
APPARENT RANK ->

SAMPLE LOCATION:

COUNTRY -> USA
STATE -> ILLINOIS

** PENN STATE COAL DATA BASE **

** PSOC-022 **
** 01/06/78 **
** PAGE 2 **

* * * * * C H E M I C A L D A T A * * * * *

PROXIMATE ANALYSIS	AS REC'D	DRY	DAF	DMMP(PARR)
% MOISTURE	17.69			
% ASH	8.35	10.14		
% VOLATILE	31.66	38.46	42.80	41.78
% FIXED CARBON	42.30	51.39	57.20	58.22

ULTIMATE ANALYSIS	AS REC'D	DRY	DAF	DMMP(PARR)	ELEMENTAL ANALYSIS	DRY	DMMP(MOD.P)	DMMP(DIR.)
% ASH	8.35	10.14		(12.38%MM)			(11.88%MM)	(%MM)
% CARBON	58.26	70.78	78.77	80.78	% CARBON	70.53	80.03	
% HYDROGEN	4.30 (*)	5.22	5.81	5.96	% HYDROGEN	5.12	5.81	
% NITROGEN	1.14	1.39	1.55	1.59	% NITROGEN	1.39	1.58	
% TOTAL SULFUR	2.13	2.59	2.88		% ORGANIC SULFUR	1.63	1.85	
% OXYGEN(DIFF)	8.13 (*)	9.88	10.99	11.68	% OXYGEN(DIFF)	9.46	10.73	
					% MINERAL MATTER (INCL. 1.67% PES2)	11.88		

(*) -EXCLUDES MOISTURE

SULFUR FORMS	% PYRITIC	% SULFATIC	% ORGANIC	% TOTAL
DRY	0.89	0.07	1.63	2.59
DAF	0.99	0.08	1.81	2.88

DRY % CHLORINE = 0.0 DRY % CO2 = 0.93

MOTT-SPOONER DIFFERENCE = -185.

CALORIFIC VALUE (GROSS, BTU/LB)	DRY	AS REC'D MOIST.	EQUIL. MOIST.	ATOM RATIOS (DMMP)	PARR	MOD.PARR	DIRECT
MM-CONTAINING	12675.	10433.		ATOMIC H/C	0.8858	0.8719	
MM-FREE (PARR)	14317.	11497.		ATOMIC O/C	0.1086	0.1007	
MM-FREE (MOD. P)	14329.	11519.					
NET CV, DMMP BTU/LB	13780.						

SAMPLE IDENTIFICATION:

PSU NUMBER -> PSOC-022
 SEAM NAME -> ILLINOIS #6
 ALTERNATE SEAM NAME ->
 APPARENT RANK ->

SAMPLE LOCATION:

COUNTRY -> USA
 STATE -> ILLINOIS

** PENN STATE COAL DATA BASE **

** PSOC-022 **
 ** 01/06/78 **
 ** PAGE 3 **

***** RANK CALCULATIONS *****

APPARENT RANK (AS REC'D MOIST.) -> INTERNATIONAL RANK :
 ASTM RANK (EQUIL. MOIST.) -> AS REC'D MOIST. ->
 REFLECTANCE RANK CATEGORY -> HVC EQUIL. MOIST. ->
 REPORTED RANK : -> HVC

***** PETROGRAPHIC DATA *****

MACERAL COMPOSITION (WHITE LIGHT ANALYSIS)

	VITRINITE	PSEUDO-VITRINITE	FUSINITE	SEMI-FUSINITE	MACRINITE	MICRINITE	SCLERO-TINITE	SEORINITE	RESINITE	ALGINITE	CUTINITE	
DMMP VOL. %	88.4	0.0	1.6	1.4	1.8	2.4	0.0	4.4	0.0	0.0	0.0	
DRY VOL. %	82.8	0.0	1.5	1.3	1.7	2.2	0.0	4.1	0.0	0.0	0.0	6.4 % MM

REFLECTANCE DATA VITRINITE : HIGH: 0.58 LOW: 0.37 MEAN-MAX: 0.49

VITRINITE TYPES V 3 V 4 V 5
 PERCENT 1.1 54.6 44.3

***** C A K I N G A N D M E C H A N I C A L P R O P E R T I E S *****

BETHLEHEM COAL PLASTOMETER:

BONDING TEMPERATURE
 TEMP. MAX. FLUIDITY
 SOLIDIFICATION TEMP.
 FLUID TEMP. RANGE
 MAXIMUM FLUIDITY

GRAY-KING COKE TYPE

HARDGROVE GRINDABILITY 57.4
 FREE SWELLING INDEX
 VICKER'S HARDNESS NUMBER 12.6

WASHABILITY DATA AVAILABLE? NO

SAMPLE IDENTIFICATION:

PSU NUMBER -> PSOC-022
SEAM NAME -> ILLINOIS #6
ALTERNATE SEAM NAME ->
APPARENT RANK ->

SAMPLE LOCATION:

COUNTRY -> USA
STATE -> ILLINOIS

** PENN STATE COAL DATA BASE **

** PSOC-022 **
** 01/06/78 **
** PAGE 4 **

MAJOR ELEMENT ANALYSIS

% HTA = 13.11

	SI02	AL2O3	TIO2	FE2O3	MGO	CAO	NA2O	K2O	P2O5	SO3
OXIDE % OF HTA	44.8	21.4	1.00	12.3	1.30	8.39	0.26	2.21	0.20	4.00
	SI	AL	TI	FE	MG	CA	NA	K	P	S
ELEMENT % OF TOTAL DRY COAL	2.7	1.5	0.08	1.1	0.10	0.79	0.03	0.24	0.01	2.59

TRACE ELEMENT ANALYSIS

% HTA = 13.11

	PPM HTA	PPM TOTAL COAL		PPM HTA	PPM TOTAL COAL		PPM HTA	PPM TOTAL COAL	VOLATILES -----	PPM TOTAL COAL
AG	< 1.0	< 0.1	GE	68.	9.	SN	< 10.	< 1.	AS	
B			LA	< 20.	< 3.	SR			BR	
BA			LI			TH			CD	
BE	16.	2.	MN			U			CL	<100.
BI	< 20.	< 3.	MO			V	170.	22.	F	
CE	<100.	< 13.	NB	< 20.	< 3.	Y	36.	5.	HG	
CO	< 20.	< 3.	NI	160.	21.	YB	8.0	1.0	SB	
CR	200.	26.	PB	200.	26.	ZN			SE	
CU			RB			ZR	220.	29.		
GA	30.	4.	SC	27.	4.					

SAMPLE IDENTIFICATION:

PSU NUMBER -> PSOC-022
SEAM NAME -> ILLINOIS #6
ALTERNATE SEAM NAME ->
APPARENT RANK ->

SAMPLE LOCATION:

COUNTRY -> USA
STATE -> ILLINOIS

** PENN STATE COAL DATA BASE **

** PSOC-022 **
** 01/06/78 **
** PAGE 5 **

SURFACE AREA AND DENSITY DATA (ALL DATA ON 40 X 70 MESH COAL)

SURFACE AREAS (SQ. M/G, MM-FREE) NITROGEN (77 DEG K) : 99.0 CARBON DIOXIDE (298 DEG K) : 189.

CHAR REACTIVITY (MAXIMUM REACTIVITY OF 1000 DEG C. , 40 X 100 MESH COAL CHARS)

AIR (1 ATM., 405 DEG. C) 0.34
CARBON DIOXIDE (1 ATM., 900 DEG. C) 0.59
HYDROGEN (27 ATM., 980 DEG. C) 1.30