

# EFFECTS OF INORGANIC CHANGES CAUSED BY NATURAL WEATHERING ON THE COMBUSTION BEHAVIOR OF BITUMINOUS COALS

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## INTRODUCTION

Weathering/oxidation is a process that can occur when coal is exposed to the atmosphere following mining and, in some instances, while it is still in the seam (outcropping). Weathering causes changes in the organic, inorganic and physical structure of coals. These structural changes can alter significantly the utilization behavior of the coals<sup>(1,2)</sup>. The most adverse effect of oxidation is probably experienced in the coking industry. Although attempts have been made to understand the mechanism of oxidation, and to elucidate the structural changes to the organic phase accompanying oxidation,<sup>(3,4,5)</sup> the reactions are still poorly understood and methods to suppress oxidation are often rather primitive<sup>(6)</sup>. Even though 70% of the coal mined in U.S is burnt in electric utility boilers, very little attention has been paid to the effects of weathering/oxidation/storage on combustion behavior. A few published studies<sup>(7,8)</sup> indicate that weathering/oxidation is detrimental to combustion in terms of carbon conversion. In addition, acid rain legislation is expected to increase the demand for low sulfur coals and therefore, electric utilities have begun to test blending strategies. As a result, coal suppliers have started blending fresh and naturally weathered/oxidized coals, because the latter generally have lower sulfur contents (for the reasons discussed later in the paper) than their fresh counterparts. Although desulfurization by weathering/oxidation may be desirable from an emissions point of view, the effects of the accompanying structural changes on combustion are not well established.

The structural differences between the organic phases and the relative combustion behavior of five outcrop coals and their fresh companions have been reported elsewhere<sup>(9)</sup>. The mineral matter is important from at least two aspects; its role in the combustion process itself and the operation and maintenance of combustion equipment (slagging, fouling and ash handling). It is known that inorganic species have a significant effect on the reactivity of coal chars to air depending on the amount, type and state of the species and rank of the coal. In this paper some of the changes in the inorganic species accompanying natural weathering, and their influence on the combustion process are discussed. A brief discussion on the likelihood of operational consequences due to these changes is also provided.

## Unique Nature of Naturally Weathered Crop Coals

Inorganic matter in coals is basically present in two forms - as discrete mineral matter which are particles of micron size or larger and as inorganic metal cations bonded to organic matter. It is known that low rank coals contain as much as 30 - 40% of the inorganic matter bound to the organic structure. On the other hand high rank coals contain mostly discrete mineral matter. Compositionally, a decrease in oxygen content is accompanied by a change in the relative amounts of the various oxygen containing functional groups. Oxidation, a process by which oxygen is introduced into the coal structure, may therefore reinstate some coal properties and behavior which were eliminated by progressive coalification. A decrease in carbon content and heating value and an increase in volatile matter, oxygen content and oxygen functional groups, and loss of coking properties lead to a lower apparent rank of a weathered coal compared to its fresh companion. On the other hand an increase in the aromaticity and sometimes a small increase in reflectance give the appearance of increasing the rank of a coal upon oxidation.

The samples used in this study were obtained from two active mines in Pennsylvania (Fort Palmer and N.S.M #2) and their companion crop coals were taken from the same seams. The naturally weathered samples are termed "crop" coals in keeping with practical mining terminology. These samples were ground to utility grind specifications (80% through 200 mesh) and then sealed under a nitrogen atmosphere in polyethylene bags until used. The time - temperature history during weathering for these samples is not known. Two other samples were obtained from the Penn State/DOE Coal Data Bank. The fresh sample was PSOC 1448 (York Canyon seam, New Mexico) and the corresponding weathered sample was from a surface of the same seam partially mined and exposed to the atmosphere for about 20 years.

## EXPERIMENTAL

Proximate analyses were performed on a Leco MAC 400 analyzer using the standard procedure. For carbon, hydrogen and nitrogen measurements, a Leco CHN 600 analyzer was used. Total sulfur was measured on a Leco Sulfur Analyzer.

### Char Preparation and Measurement of Reactivity

Preparation of the chars and measurement of the reactivity were performed in a thermogravimetric analyzer (Perkin Elmer Series 7 Thermal Analyzer). The sample size used was  $5 \pm 0.5$  mg. The experiments involved a multistep procedure. The furnace was purged with nitrogen for one hour and heated from room temperature to  $110^\circ\text{C}$  at the rate of  $20^\circ\text{C}/\text{min}$  and held at  $110^\circ\text{C}$  for 5 minutes. The temperature was then ramped to  $930^\circ\text{C}$  at the rate of  $40^\circ\text{C}/\text{min}$  and held at  $930^\circ\text{C}$  for 7 minutes in order for devolatilization to take place. The temperature of the furnace was reduced to  $450^\circ\text{C}$  at  $50^\circ\text{C}/\text{min}$  and allowed to thermally stabilize at  $450^\circ\text{C}$  for 10 minutes. The heating sequence above was conducted in a nitrogen atmosphere. The reactivity of the char thus produced was determined at  $450^\circ\text{C}$  (723 K) in one atmosphere of air. The change in the weight of the sample with time was recorded.

To determine the effect of mineral matter on the reactivity of the companion fresh and crop coal samples, about 10 grams of each coal were acid washed with 100 ml of 10% HCl for 24 hours at about  $60^\circ\text{C}$ . The samples were then filtered and washed thoroughly with distilled water until the filtrate was free of chloride ions (i.e. produced no precipitate with  $\text{AgNO}_3$  solution). The residue was then dried overnight in a vacuum oven at  $50^\circ\text{C}$  and stored for subsequent reactivity measurements.

### Chemical Analyses of the Inorganic Species

Chemical analyses were performed on the samples of ash produced by ashing coals in a Leco proximate analyzer (MAC 400) at  $750^\circ\text{C}$ . Determination of all the major elements was performed using the atomic absorption technique described by Meddlin et al.<sup>(10)</sup>.  $\text{SO}_3$  was determined using a Leco Sulfur titrator. The acid wash extracts were analyzed for sodium, potassium, calcium, barium, magnesium and iron by spectrochemical - Lithium metaborate fusion into solution on a Spectrometrics Spectraspan III D.C. plasma Spectrometer with a CDAC 360 Data Acquisition System.

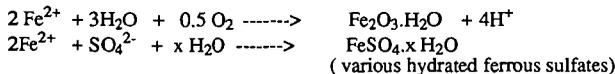
Qualitative mineralogical analysis was performed using a Rigaku X - ray Diffractometer with the low temperature ashes produced from the coals. Ash fusion temperatures were determined using a Leco - AF600 Ash Fusion Determinator.

## RESULTS AND DISCUSSION

Proximate and elemental analyses of the samples are given in Table 1. The N.S.M.#2, Fort Palmer and New Mexico fresh coals have ranks of low volatile, medium volatile and high volatile bituminous (ASTM), respectively. Differences in chemical composition between the fresh and the crop coals have been discussed in detail elsewhere<sup>(9)</sup>. The most important difference pertaining to inorganics is the lower sulfur content of the crop coals relative to their fresh companions by about 20 - 80%. This is due mainly to the oxidation of pyrite in the coals. The difference in sulfur content between the N.S.M.#2 fresh and crop coals was about 80% (3.24 versus 0.68%), whereas it was only about 20% (0.51 versus 0.41%) for the New Mexico samples because of a very low pyritic sulfur content of this coal (0.05%). The sulfatic and organic sulfur contents were 0.01 and 0.45% respectively. Table 2 lists the qualitative mineralogical analysis of the fresh and the crop coals. The data confirmed the absence of pyrite in the Fort Palmer and New Mexico weathered samples. Similarly, a lower pyrite content was observed for N.S.M.#2 crop coal relative to its fresh companion. Desulfurization by oxidation of pyrite has been reported in the literature<sup>(11)</sup>. Chandra et al.<sup>(11)</sup> reported a 93% decrease in pyritic sulfur (from 0.89 to 0.06%) accounting for 92% of the total sulfur reduction due to weathering over a four year period. This desulfurization process is believed to take place as follows<sup>(12)</sup>



and



Some of the ferrous sulfates, being soluble in water, and sulfuric acid are responsible for acid mine drainage. However, iron sulfates such as szolmolnokite are insoluble in water.

It can be seen from Table 1 that the ash contents of the weathered coals are lower and higher than their fresh companions, i.e. there is not a definite trend. This can be explained as follows. The weight of the oxidized minerals depends on the form of iron after oxidation (for example  $\text{FeSO}_4$  or  $\text{Fe}_2\text{O}_3$ ) and the extent of oxidation. The acidic water may also lead to leaching of some of the acid soluble components such as calcite and depending on the acidity, some of the clay minerals may also be leached. It can be seen from Table 2 that the New Mexico Fresh sample contained calcite but the oxidized companion did not and that the ash content of the crop coal was lower than that of fresh sample due to leaching. Table 3 gives the compositional analysis of the ash samples of the fresh, crop and acid washed samples. It is noted from Table 3 that the amount of iron per unit weight of coal in the Fort Palmer and N.S.M.#2 weathered samples is higher than in their fresh companions as is their ash contents (dry basis). This suggests that the iron sulfates formed by the oxidation of pyrite in these coals are insoluble (such as szolmolnokite) and therefore the iron was not leached out. The reduction in sulfur in the two Pennsylvania crop coals was due to sulfuric acid drainage. A reduced iron content in the New Mexico weathered sample is probably due to the formation of soluble iron sulfates.

### Reactivity of the Fresh and the Crop Coals

The coal samples were pyrolyzed in a nitrogen atmosphere as described earlier. The resultant chars were stabilized thermally at  $450^\circ\text{C}$  for 10 minutes and were then reacted with air at  $450^\circ\text{C}$  until at least 50% burnoff (d.a.f. basis). The first derivative of the weight versus time curve was plotted as a function of time and a typical curve is shown in Fig.1 for the Fort Palmer fresh, crop and acid washed coals. Various parameters have been used in the literature to express the reactivity of coal chars<sup>(13,14,15)</sup>. Since the burnoff time of the particle is the ultimate indicator of its reactivity, the time for 50% burnoff (d.a.f. basis) of the char was used in this study as a measure of reactivity. The time required for 50% burnoff of the fresh, crop and acid washed fresh and crop coal chars is listed in Table 4. The times required for 50% burnoff were reproducible to within  $\pm 3$  min. In all cases, the time for 50% burnoff for the crop coal chars was found to be lower than that of the corresponding fresh sample. The higher reactivity of crop coals cannot be explained by the increase in the total and accessible surface areas as discussed elsewhere<sup>(9)</sup>. Therefore, an alternative explanation is provided here.

### Possibility of Catalytic Activity in the Crop Coal Chars

It has been reported that mineral matter plays an important role in the reactivity of coal chars to various gases<sup>(14,16-18)</sup> depending on the rank of the coal precursor and the state and type of inorganic species present. Jenkins et al.<sup>(14)</sup> correlated reactivity with CaO and MgO contents although the state in which the elements were present was not reported. No correlation was obtained between the reactivity and the potassium, sodium and iron contents.

Depending on the local environment, oxygen partial pressure, moisture content, the chemical nature of the overburden, the concentration of ion - exchangeable cations and pH of the percolating water, there is a possibility of some cations being bound to the carboxylic functional groups produced during weathering. Since there was an indication of the presence of salts of carboxylic acids in the DRIFT spectra of the crop coals<sup>(9)</sup> and also a significantly higher CaO content in the Fort Palmer crop coal ash (16.5%) compared to that in its fresh companion coal ash (0.81%), and a substantially higher iron content in the N.S.M.#2 crop coal ash (38.6%) compared to that in its fresh coal ash (23.9%), some catalytic activity due to these differences was suspected.

Figure 2 shows a plot of the time required for 50% char burnoff (d.a.f. basis) as a function of the calcium oxide content in the coal. It can be seen that there is a trend of increasing reactivity with increasing calcium oxide content in the coal for both the weathered and fresh coals. This is similar to the trend observed by Jenkins et al.<sup>(14)</sup>.

A separate reactivity test was conducted to determine the influence of catalytic activity on the reactivity of the samples. Times required for 50% burnoff on d.a.f. basis ( $T_{50\%}$ ) were obtained for the acid washed fresh and crop coal samples and are listed in Table 4. On examining the effect of acid washing on the reactivity of the fresh coals, in which no catalytic activity is expected, it was observed that there was an increase in the reactivity of N.S.M.#2 and Fort Palmer fresh coal chars upon acid washing. This shows that the reactivity of a char is a complex phenomenon which depends on the combined effects of the change in physical structure and the chemical nature of the coal. The ranks of these two coals are low and medium volatile bituminous, respectively. For such high rank coals with low porosity, the alteration of the pore system by acid washing increases the accessibility of oxygen into the pore structure. The effect of an increase

in the number of 'feeder pores' is significant compared to the reduction of the catalytic activity due to the removal of inorganic species upon acid washing, and hence, there is a net increase in the reactivity of the N.S.M.#2 and Fort Palmer fresh coals. Jenkins et al.<sup>(14)</sup> reported such a phenomenon for a low volatile bituminous coal (PSOC 127). Also, Mahajan and Walker<sup>(19)</sup> found an increase in the nitrogen and carbon dioxide surface areas for a low volatile bituminous coal char (from PSOC 127) by factors of 2 and 3, respectively upon removing the mineral matter from the coal. From Table 4 it is also noted that for the New Mexico coal the  $T_{50\%}$  of fresh sample increased marginally upon acid washing. This is again in concurrence with the observations of Mahajan and Walker<sup>(19)</sup> of no significant difference in the surface areas of raw and acid washed, high volatile bituminous coal chars. The marginal decrease in the reactivity of the New Mexico fresh sample upon acid washing, could also be due to the removal of catalytically active inorganic species.

It was also observed that acid washing reduced the reactivity and thereby increased the  $T_{50\%}$  for all the crop coals reported. The  $T_{50\%}$  for the acid washed crop coal was almost twice that of the crop sample for the Fort Palmer coal (59 compared to 26 min) and the New Mexico coal (75 compared to 46 min), whereas the  $T_{50\%}$  for N.S.M.#2 acid washed crop sample was only 13% higher (119 compared to 105 min) than that of the crop coal. In light of the above discussion, this significant decrease in the reactivity of the acid washed Fort Palmer crop char was a result of the removal of inorganic species, despite the likely attendant increase in the number of 'feeder pores'. This indicates a significant contribution by the inorganic species to the reactivity of the Fort Palmer crop sample. The reactivity of the New Mexico crop sample also decreased upon acid washing and this is attributed to the removal of catalytic species during acid washing since the surface area change was found to be negligible for the high volatile bituminous coal chars<sup>(19)</sup>. The reactivity decrease or the increase in the  $T_{50\%}$ , in the case of the N.S.M.#2 acid washed crop sample was not very high. This is attributed to the type of catalytic species present in the coal. Table 5 gives the spectrochemical analysis of the acid extracts. The species present in significant proportions relative to those in the fresh coal extracts were calcium, magnesium and iron in the case of the Fort Palmer coal. Although some minerals such as calcite and gypsum are acid soluble, such minerals are known to be catalytically inactive<sup>(20)</sup>. Hence, the catalytic activity in the Fort Palmer and New Mexico crop coals was attributed mainly to the presence of ion-exchangeable calcium since this cation is known to be highly catalytic towards gas - carbon reactions<sup>(17,21)</sup>. In the case of the N.S.M.#2 crop coal acid washing extract, a significant proportion of iron was found compared to that in the extract from the fresh coal and since some of the iron was present in sulfate form, the catalytic activity could be due to iron in ferrous form. However, during the carbon - oxygen reaction, iron is oxidized to ferric oxide and loses its catalytic activity quickly. The slope of the weight change curve for the N.S.M.#2 crop coal was initially high and then dropped off to a lower value as can be seen from Fig. 3. The slope of the curve for the N.S.M.#2 acid washed sample tended to be more linear. As previously noted, the catalytic activity of iron depends on the ratio of ferrous to ferric and how quickly ferrous is oxidized to ferric. This explains the smaller decrease in reactivity (only 13%) on acid washing the N.S.M.#2 crop sample.

#### Effect of Changes in Mineral Matter on Operational and Handling aspects

The nature and amount of inorganic matter in coal are important considerations in the design of a coal fired boiler. These influence fouling of convective heat transfer surfaces and affect heat transfer characteristics. The potential for slagging and fouling depends on the inorganic constituents and the temperature they attain during combustion. A reduction in acidic oxides ( $\text{SiO}_2$ ,  $\text{Al}_2\text{O}_3$  and  $\text{TiO}_2$ ) and an enrichment in  $\text{CaO}$  (from 0.8 to 16.5%) was observed for Fort Palmer crop coal ash compared to the ash from the fresh sample. Other alkali oxides such as  $\text{K}_2\text{O}$  and  $\text{Na}_2\text{O}$  did not show any significant change. Similarly, a higher iron content was noted in the N.S.M.#2 weathered sample (23.9 to 38.6%). The New Mexico ash samples did not indicate any major differences that could affect the behavior of the ash in a boiler. An increase in the basic oxides in an ash usually indicates an increased potential for fouling and slagging. Many empirical indices have been proposed to predict slagging and fouling<sup>(22)</sup>. The ASTM fusion temperature determination, although purely empirical, was developed to measure the clinkering tendency of coal ash on a grate, but it is still widely used as a method for determining ash fusibility. The ash fusion temperatures for the fresh and crop coal samples are listed in Table 6. The initial deformation temperature (I.D.T.) of the Fort Palmer crop ash is about 430° F lower than for the corresponding fresh coal ash. Similarly, the Hemispherical Temperature (H.T.) is about 250° F lower than for the corresponding fresh coal ash. Although the I.D.T. of the crop coal ash is relatively low it is still high enough for use in a dry bottom furnace. The fusion temperature for the New Mexico crop sample is also lower than that of its fresh companion ash by about 250° F. The difference in fusion temperatures for N.S.M.#2 crop and fresh samples is not significant. The slagging and fouling indices defined by Attig and Duzy<sup>(23)</sup> (base/acid ratio times coal sulfur and base/acid ratio times sodium content,

respectively) were also calculated and are listed in Table 7. They are within the values generally recommended for trouble free operation.

## CONCLUSIONS

Weathering causes desulfurization of coals primarily through oxidation of pyrite and the reduction in sulfur has a direct impact on  $\text{SO}_x$  emissions from combustors. Some of the metal cations are incorporated into the organic structure as ion-exchangeable cations which catalyze the combustion reactions and thereby increase the heat release rate. The composition of the ash from weathered coals indicates a significant concentration of fluxing agents such as  $\text{CaO}$  and  $\text{Fe}_2\text{O}_3$  which is reflected in the relatively low fusion temperatures. Although the empirical parameters used to predict slagging and fouling are within safe limits, caution should be exercised when burning these crop coals.

## REFERENCES

1. Huggins, F. E., Huffman, G. P., Dunmyre, G. R., Nardozi, M. J. and Lin, M. C., *Fuel Processing Technology*, 1987, vol. 15, pp. 233 - 244.
2. Gray, R. J., Rhoades, A. H. and King, D. T., *Trans. Of Soc. of Min. Engrs., AIME*, 1976, Vol. 260, pp. 334 - 341.
3. Wachowska, H. M., Nandi, B. N. and Montgornery, D. S., *Fuel*, 1974, Vol. 53, p. 212.
4. Liotta, R., Brons, G. and Isaacs, J., *Fuel*, 1983, Vol. 62, p. 781.
5. Rhoads, C. A., Senftle, J. T., Coleman, M. M., Davis, A. and Painter, P., *Fuel*, 1983, Vol. 62, p. 1387.
6. Gaines, A. F., in "New Trends in Coal Science", NATO Series, Kluwer Academic Publishers, The Netherlands, 1988, p. 206.
7. Nandi, B. N., Brown, T. D. and Lee, G. K., *Fuel*, 1977, Vol. 56, No. 4, pp. 125-130.
8. Lee, G. K. and Whaley, H., *J. of Inst. of Energy*, 1983, Vol. 12, pp. 191-197.
9. Pisupati, S. V., Scaroni, A. W. and Stoessner, R. W., "Combustion Characteristics of Naturally Weathered (Insitu) Bituminous Coals", submitted to *Fuel Processing Technology*
10. Meddlin, J. H., Suhr, N. H. and Bodkin, J. B. *Atom. Abs. News*, 1969, vol. 8, p. 25.
11. Chandra, D., Chakrabarti, J. N. and Swamy, Y. V., *Fuel*, 1982, Vol. 61, pp. 204 - 205.
12. Berkowitz, N., in "Sample Selection, Aging and Reactivity of Coal", Klen, R. and Wellek, R (eds), John Wiley & Sons, N.Y., 1989, P. 226.
13. Walker, P. L., Jr., and Hippo, E. J., *Div. of Fuel Chem., Am. Chem. Soc.*, 1977, Vol 20, pp. 45 - 51.
14. Jenkins, R. G., Nandi, S. P. and Walker, P. L., Jr., *Fuel*, 1973, Vol. 52, pp. 288 - 293.
15. Tomita, A., Mahajan, O. P. and Walker, P. L., Jr., *Fuel*, 1977, Vol.56, pp. 137 - 144.
16. Walker, P. L., Jr., Shelef, M. and Anderson, R. A., "Chem. and Phy. of Carbon", Walker, P.L., Jr., (Ed.), 1969, Vol. 4, Marcell Dekker Inc., N.Y., pp. 287 - 383.
17. Morgan, B. A. and Scaroni, A. W., "Pulverized Lignite Combustion", *Int. Conf. on Coal Sci., Int Energy Agency, Sydney, Australia*, 1985.
18. Radovic, L. R., Walker, P. L., Jr. and Jenkins, R. G., *Fuel*, 1983, Vol. 62, pp. 209 -212.
19. Mahajan, O. P. and Walker, P. L., Jr., *Fuel*, 1979, Vol. 58, pp. 333 - 337.
20. Tomita, A., Mahajan, O. P. and Walker, P. L., Jr., *Div. of Fuel Chem., Am. Chem. Soc.*, 1977, Vol. 22, pp. 4 - 6.
21. Hippo, E. J., "The Effect of Cation Exchange on the Subsequent Reactivity of Lignite Chars to Steam", Ph.D Thesis, 1977, The Pennsylvania State University.
22. Sondreal, E. A., Tufte, P. H. and Beckering, W., *Comb. Sci. and Tech.*, 1977, Vol. 16, pp. 95 - 110.
23. Attig, R. C. and Duzy, A. F., "Coal Ash Deposition Studies and Application to Boiler Design", *Am. Power Conf.*, April 1969.

TABLE 1  
Proximate Analysis (as determined) Wt%

Mine	Moisture	Ash	F.C. (d.m.m.f)	V.M. (d.m.m.f)	Rank (A.S.T.M)
N.S.M. #2 Fresh	0.54	8.70	79.06	20.94	I.v.bit.
N.S.M. #2 Crop	4.44	9.19	75.50	24.50	m.v.bit.
Fort Palmer Fresh	0.72	13.43	75.94	24.06	m.v.bit.
Fort Palmer Crop	8.34	15.91	67.19	32.81	sub.bit.A
New Mexico Fresh	1.48	11.27	60.17	39.82	h.v.A.b
New Mexico Crop	7.29	6.07	60.83	39.16	h.v.A.b

Elemental Analysis on dry, mineral matter free basis

Mine	Carbon	Hydrogen	Nitrogen	Sulfur	Oxygen(by diff.)
N.S.M. #2 Fresh	90.23	4.68	1.56	3.24	0.29
N.S.M. #2 Crop	86.11	4.04	1.47	0.68	7.70
Fort Palmer Fresh	89.61	5.04	1.83	2.09	1.43
Fort Palmer Crop	82.05	3.90	1.66	1.24	11.15
New Mexico Fresh	87.29	5.63	1.64	0.51	4.93
New Mexico Crop	78.66	4.24	1.70	0.41	14.99

TABLE 2  
Qualitative Mineralogical Analysis

Mineral	N.S.M.#2 Fr	N.S.M.#2 Cr	F.P. Fr	F.P. Cr	N.M. Fr	N.M. Wea.
Kaolinite	X	X	X	X	X	X
Quartz	X	X	X	X	X	X
Pyrite	X	X	X	--	X	--
Illite			--	X		
m.l.c			X	--		
Calcite					X	--
Bassanite			--	X		
Fe sulfates			--	X		
Feldspars	--	X	X	--		

Fr = Fresh, Cr = Crop and Wea = Weathered

TABLE 3

Analyses of the Ashes ( wt%)

Oxide	FPF	FPW	NSMF	NSMW	NMF	NMW	FPFAW	FPWAW	NMFAW	NMFAW
SiO <sub>2</sub>	55.9	38.3	43.2	34.5	40.5	37.2	61.0	58.0	65.0	57.4
Al <sub>2</sub> O <sub>3</sub>	26.9	20.2	25.6	22.1	23.9	29.0	27.8	29.4	29.6	32.4
TiO <sub>2</sub>	1.42	0.96	1.46	0.98	1.06	1.36	1.45	1.57	1.68	1.84
Fe <sub>2</sub> O <sub>3</sub>	10.3	9.31	23.9	38.6	7.00	9.02	6.89	5.99	1.88	2.55
MgO	0.59	1.33	1.12	0.48	2.11	2.97	0.48	0.7	0.49	0.96
CaO	0.81	16.5	2.71	1.24	15.7	11.0	0.26	1.53	0.48	2.17
MnO	0.02	0.03	0.03	0.02	0.01	0.02	0.01	0.01	0.01	0.01
Na <sub>2</sub> O	0.57	0.45	0.22	0.22	1.09	2.13	0.61	0.85	0.74	1.41
K <sub>2</sub> O	2.08	1.65	2.11	2.11	0.54	0.79	2.09	2.63	0.85	0.61
P <sub>2</sub> O <sub>5</sub>	0.38	0.41	0.3	0.18	1.39	1.67	#	#	#	#
SO <sub>3</sub>	0.1	10.9	<0.05	<0.05	5.5	*	<0.05	<0.05	<0.05	<0.06
Total	99.1	100.0	100.7	99.4	98.8	95.2	100.6	100.7	100.7	100.0

FPF : Fort Palmer Fresh    FPW : Fort Palmer Crop    NSMF: N.S.M.#2 Fresh    NSMW: N.S.M.#2 Crop  
 NMF: New Mexico Fresh    NMW: New Mexico Weathered    FPF AW: Fort Palmer Fresh, Acid Washed    FPW AW: Fort Palmer Crop, Acid Washed  
 NMF AW: New Mexico Fresh, Acid Washed    NMW AW: New Mexico Weathered, Acid Washed

TABLE 4  
Times for 50% Burnoff of Char (d.a.f. basis, min)

Sample	Original Coal Char	Acid Washed Coal Char
Fort Palmer Fresh	345	242
Fort Palmer Crop	26	59
N.S.M.#2 Fresh	668	572
N.S.M.#2 Crop	105	119
New Mexico Fresh	98	102
New Mexico Crop	46	75

TABLE 5  
Spectrochemical Analysis of the Acid Extracts

Cation	Concentration ( $\mu$ g / g of daf coal)					
	F.P. Fr.	F. P. Cr.	N.S.M.#2 Fr.	N.S.M.#2 Cr.	N.M. Fr.	N.M. Cr
Barium	82	181	47	144	555	580
Calcium	660	16634	608	1616	11786	4323
Iron	3690	9826	5891	13464	4853	3396
Potassium	260	470	140	287	372	438
Magnesium	140	1184	NA	NA	1450	988
Sodium	188	140	65	45	693	618

TABLE 6  
Ash Fusion Temperatures ( ° F )

Sample	Initial Deformation	Softening	Hemispherical	Fluid
Fort Palmer Fresh	2775	2805	2830	2845
Fort Palmer Crop	2340	2375	2470	2590
N.S.M. # 2 Fresh	2540	2570	2595	2600
N.S.M. # 2 Crop	2540	2555	2560	2565
New Mexico Fresh	2435	2465	2480	2500
New Mexico Crop	2215	2405	2420	2425

TABLE 7  
Slagging and Fouling Indices \*

Sample	Slagging Index	Fouling Index
Fort Palmer Fresh	0.35	0.10
Fort Palmer Crop	0.61	0.22
N.S.M.#2 Fresh	1.39	0.10
N.S.M.#2 Crop	0.50	0.16
New Mexico Fresh	0.20	0.44
New Mexico Crop	0.16	0.94

\* Attig and Duzy (23)

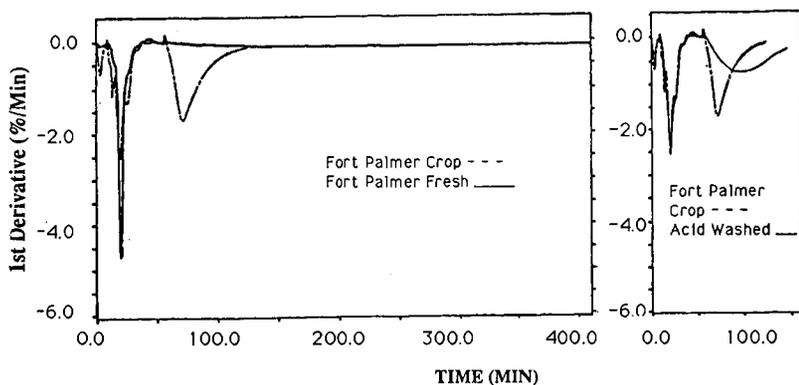


FIG.1. RATE OF WEIGHT LOSS (DERIVATIVE) AS A FUNCTION OF TIME FOR FORT PALMER FRESH, CROP AND ACID WASHED COALS

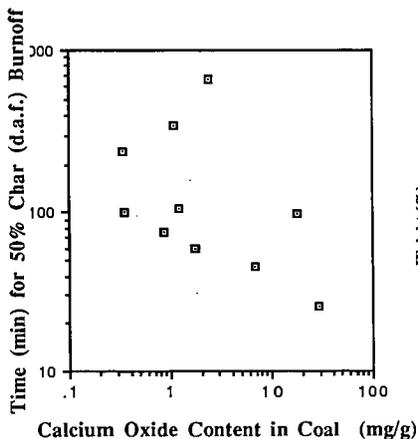


FIG.2. TIME FOR 50% BURNOFF (D.A.F.) AS A FUNCTION OF CALCIUM OXIDE CONTENT IN COAL

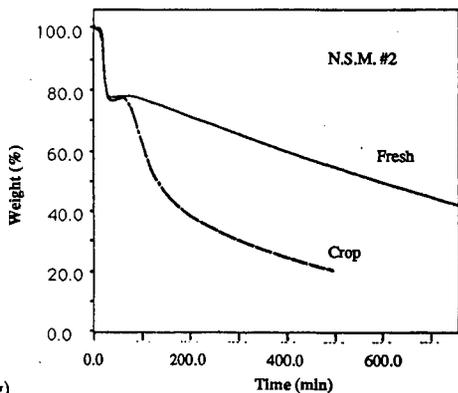


FIG.3. WEIGHT REMAINING CURVES AS A FUNCTION OF TIME FOR N.S.M. #2 FRESH AND CROP COALS