T-2844

Characterization
of
Biomass Fuel Feedstocks

by

Patricia Gabella

A thesis submitted to the Faculty and the Board of Traustees of the Colorado School of Mines in partial fulfillment ot the requirements of the degree of Master of Science (Chemical and Petroleum-Refining Engineering).

Golden, Colorado
Date December 3, 1984

Signed Patricia Gabella
Patricia Gabella

Approved Michael S Graboski
Michael S. Graboski
Thesis Advisor

Golden, Colorado
Date December 13, 1984

Kidnay
Arthur J. Kidnay
Head of Department
Chemical and Petroleum
Refining Engineering

ABSTRACT

Fifteen biomass samples, nine agricultural wastes and six wood and wood wastes, were characterized for performance in gasification and combustion applications. Proximate and ultimate analyses, higher heating values, ash elemental analyses and fusion temperatures were measured. The fuels were high in oxygen and volatiles content, low in ash and fixed carbon, had varying nitrogen, sulfur and chlorine content and had lower calorific content than coals. The elemental content in the ash of the samples varied widely (i.e. silica ranged from 96.54% to less than 4.75%). The woods had more calcium and magnesium and less silica and potassium than the agricultural wastes. The elemental data on the biomass samples were used in three coal ash fusion temperature prediction equations: Sondreal and Ellman, Bryers and Taylor and Winegartner and Rhodes. The coal equations did not consistently predict biomass ash fusion temperatures.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACKNOWLEDGEMENTS

I wish to thank Dr. Michael Graboski for his understanding, encouragement and technical guidance throughout this project. I am grateful to Stan Schoenwald and Larry Cox at the Colorado School of Mines Research Institute for their technical guidance and help with the elemental analyses. I am grateful for the assistance of Judy Fife and Debbie Hobbs in running the ash fusion analysis. Also, to Hugh Millard at U.S.G.S. for assistance and use of the nuclear reactor to run nuetron activation analysis for Cl. Last but not least, to Ron Miner and the graduate students on the fourth floor of Alderson Hall, who were willing to lend a helping hand.

DEDICATION

To my family for their love and support. To my friends for caring enough to help push me through this critical event.

1. INTRODUCTION

Biomass is a term used to describe renewable biological materials which can be used as an energy source. Usually, it refers to woods, wood wastes, agricultural wastes and biological refuse. Wood wastes include logging residues and mill wastes. Logging residue is all wood material left on the ground after harvesting (the slash and branches). Mill residue is the wood and bark byproducts produced in converting logs to primary products (Horsfield 1977). Agricultural waste is material left over after harvest of the plant is completed. These residues include straws, stalks, stems, hulls, cobs, nutshells and bagasse (Hayes 1973).

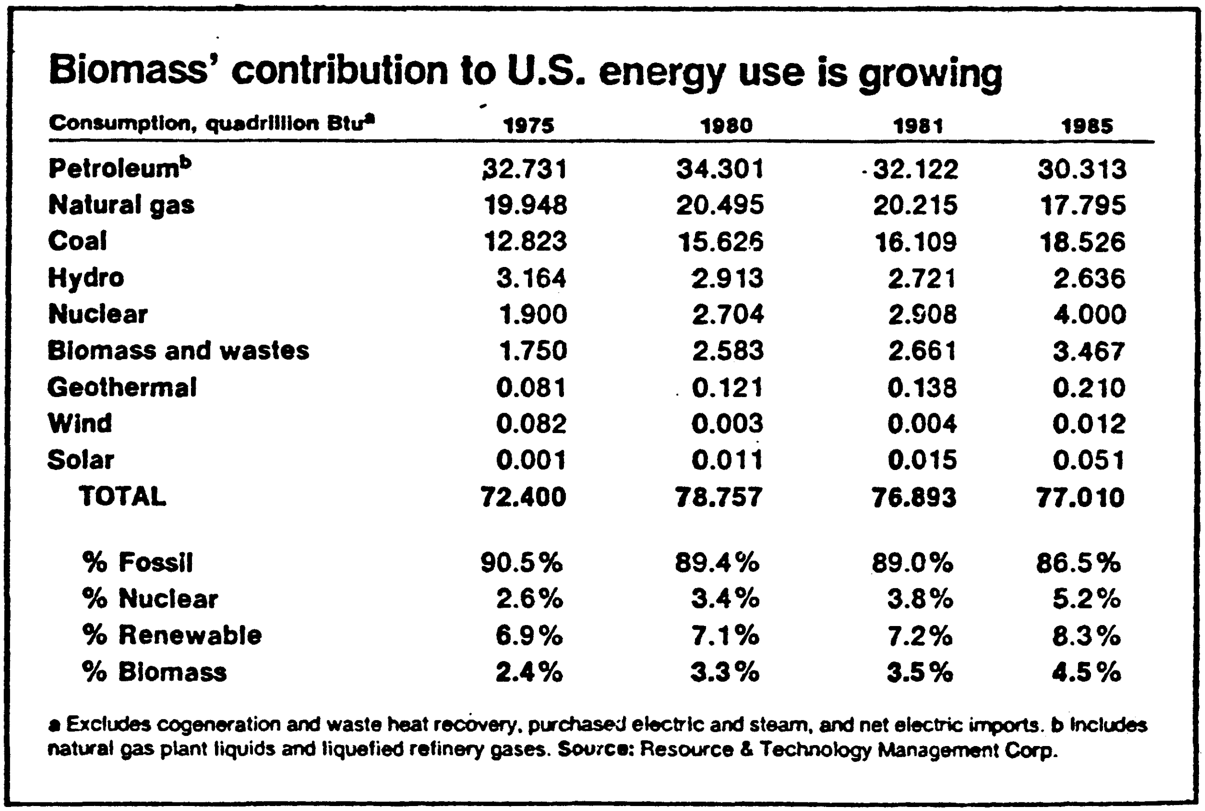
Before the discovery of petroleum and later gaseous fuels (mid - late 1800's), available biomass materials (mainly woods) were the major energy source for heating and cooking. Even today, about half the world's population relies mainly on wood for their cooking, which comprises four-fifths of the total household energy used. About half of all trees cut down are used for cooking and heating (Zsuffa 1982). More than 90% of energy drawn from the environmental sources in the mid 1800's came from wood, harnessed wind and water power (Lally 1983). After the discovery and commercial development of petroleum and gas fuels, there was a significant decrease in wood use as an energy source. Petroleum and gas were cheaper and had a much higher energy content, helping "fuel" rapid industrial growth and became a necessity of today's society. Lubricants, synthetic polymers and fibers, medicines and other necessities are not possible without hydrocarbons and their derivatives as source material (Lally 1983).

Energy for power is available through direct combustion or through gasification of biomass. Gasification can also provide hydrocarbons for feedstocks for many synthetic substances which help society and technology function. Biomass cannot replace petroleum, but its use is on the increase. Table 1 shows that in the United States, bioenergy contributes almost as much energy as nuclear or hydropower (Haggin 1983). Zsuffa (1982) states that biomass supplies about one-seventh of the world's fuel. The largest percentage of biomass on the earth is from wood in forests. In the U.S., wood is the predominate source to contribute to biomass energy (Table 2) (Haggin 1983).

Biomass has many advantages as a fuel source. Through proper management and harvesting techniques, it is a renewable resource. Generally, biomass is low in ash (with some exceptions) in comparison with coals. It has little or no nitrogen (0 - 1%) and sulfur (0 - .1%), which are

Table 1

Biomass Contributions to United States Energy



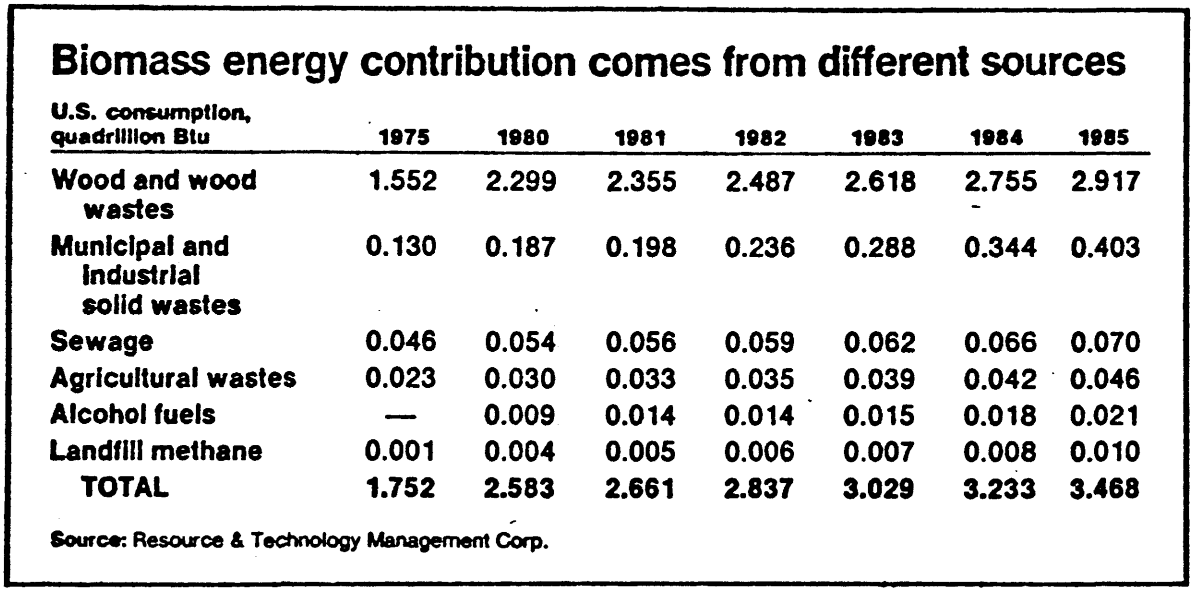
Biomass' contribution to U.S. energy use is growing

Consumption, quadrillion Btu[a]	1975	1980	1981	1985
Petroleum[b]	32.731	34.301	32.122	30.313
Natural gas	19.948	20.495	20.215	17.795
Coal	12.823	15.626	16.109	18.526
Hydro	3.164	2.913	2.721	2.636
Nuclear	1.900	2.704	2.908	4.000
Biomass and wastes	1.750	2.583	2.661	3.467
Geothermal	0.081	0.121	0.138	0.210
Wind	0.082	0.003	0.004	0.012
Solar	0.001	0.011	0.015	0.051
TOTAL	72.400	78.757	76.893	77.010
% Fossil	90.5%	89.4%	89.0%	86.5%
% Nuclear	2.6%	3.4%	3.8%	5.2%
% Renewable	6.9%	7.1%	7.2%	8.3%
% Biomass	2.4%	3.3%	3.5%	4.5%

a Excludes cogeneration and waste heat recovery, purchased electric and steam, and net electric imports. b Includes natural gas plant liquids and liquefied refinery gases. Source: Resource & Technology Management Corp.

Table 2

Sources of Biomass Energy Contribution



Biomass energy contribution comes from different sources

U.S. consumption, quadrillion Btu	1975	1980	1981	1982	1983	1984	1985
Wood and wood wastes	1.552	2.299	2.355	2.487	2.618	2.755	2.917
Municipal and industrial solid wastes	0.130	0.187	0.198	0.236	0.288	0.344	0.403
Sewage	0.046	0.054	0.056	0.059	0.062	0.066	0.070
Agricultural wastes	0.023	0.030	0.033	0.035	0.039	0.042	0.046
Alcohol fuels	—	0.009	0.014	0.014	0.015	0.018	0.021
Landfill methane	0.001	0.004	0.005	0.006	0.007	0.008	0.010
TOTAL	1.752	2.583	2.661	2.837	3.029	3.233	3.468

Source: Resource & Technology Management Corp.

major environmental pollution problems. Biomass gasifies easier then coal due to higher volatile content (70 - 90%), lower ash and higher char reactivity toward steam and CO_2 (Lally 1983). The higher heating value of woods is about 8500 BTU/lbm versus about 10000 BTU/lbm for lignite coal (Herman 1981, Lally 1983).

Disadvantages also exist with biomass fuel. The high moisture content of freshly harvested material necessitates fuel drying or poor combustion efficiencies. Ash is a particulate emissions problem, and some agricultural wastes and municipal sewage wastes have high ash contents (up to 20% and 20 - 70%, respectively) (Tillman 1978). Since biomass often exhibits low bulk density or unmanageable size, there are energy costs to consider for size reduction and densification. Transportation to a facility for use must be considered. Therefore, to keep costs down, as much material as possible should be transported or transportation should be minimzed.

The purpose of this research is to gather data on the composition and ash content of various biomass materials. Biomass can be used solely for a fuel source or can be supplementary to standard fuels, such as coal. Fuel and ash are important in evaluating utilization in combustion and gasification systems. Ash characteristics can effect power plant performance through corrosive action, fouling of boiler tubes, slagging and environmental pollution (Vaninetti 1982).

Standard coal analysis methods may be used to determine fuel characteristics of biomass. The tests include proximate analysis, ultimate analysis and higher heating value, elemental ash analysis and ash fusion temperatures. The fuel analyses give information on heating content and burning characteristics. Nitrogen, sulfur and chlorine analyses on total samples are useful since these elements are important from an environmental perspective. The ash analyses are useful for estimating ash handling (dry or slagging) and disposal problems. These experimental data are compared with data found in the literature. Coal correlations which predict ash fusion temperatures from elemental analysis data are explored. This body of work should supply a frame of reference of selected biomass ash characterisitcs, which is not readily available in the literature.

2. LITERATURE REVIEW

2.1 Fuel Analysis

There are many standard tests established for evaluating coals as a fuel: proximate analysis, ultimate analysis, higher heating content or calorific value, sulfur, chlorine and nitrogen content, mineral matter in the ash and ash fusibility. These help evaluate the performance of combustion coals as a solid fuel. Biomass fuel stocks may be analyzed with the same tests.

2.1.1 Ashing

The function of ashing is to remove the organic fraction of the sample with little or no loss of the inorganic constituents. Ashing also provides a means of oxidizing and concentrating the elements of interest (Watling 1977). Wet ashing techniques employ chemical attack to isolate the inorganic material. In dry ashing, the sample is combusted to remove the organic material.

Some advantages of using a dry ashing technique are fewer reagents are needed, it is easier to handle large volume samples and operator time per sample is shorter. Some disadvantages are: elements may be lost by volatilization or by retention on ashing containers, the equipment can be expensive and oxidation takes a long time (Greweling 1976). Watling found dry ashing gave comparable results to wet ashing for analysis of biological samples. Dry ashing gave comparable results to wet ashing for plant material on elements Fe, Mn, Ca, Mg and K analyzed by atomic absorption (Prasad 1978). Of the different dry ashing procedures reported by Lambert (1976), dry ashing without extracting siliceous material gave excellent results (repeatability) for Ca, Mg, K, Na and P. Al, F and Mn were underestimated slightly, but extraction is very time consuming and the difference was not that large to warrant extraction. Cl and F loss were not studied here, but employing methods of analysis which can utilize whole samples and not just the ash, such as nuetron activation analysis or possibly x-ray fluoresence, would provide insight on the volitilization of these elements.

2.1.2 Proximate Analysis (ASTM D3172-73 (1983))

Proximate analysis is a method of comparing and ranking coals under standard heating conditions. Proximate analysis yields an estimate of moisture, volatile matter, fixed carbon and ash content. Water is associated with coal and plant material in two forms, free water and bound water. Free water is held loosely in large capillaries and has a normal vapor pressure. Bound water is water held more firmly in the internal pore structure and has a vapor pressure lower than normal. Volatile matter is obtained during pyrolysis of coal or biomass material and consists mainly of combustible gases, hydrogen, carbon monoxide, methane and other hydrocarbons, tar vapors, and some incombustible gases such as carbon dioxide and water vapor.

Ash is the residue left after oxidation in air. The amount of ash is proportional to the amount of inorganic matter in the fuel material, though it is usually different in chemical composition. This inorganic matter comes from dirt or soil associated with the fuel material. Some inorganic matter becomes incorporated with the organic matrix upon coal bed formation or during plant growth.

The fixed carbon is the solid residue, exclusive of ash, left after drying and expulsion of the volatile matter. It is considered to be a polynuclear aromatic hydrocarbon residue resulting from condensation reactions which occur during pyrolysis. Carbon is the principal constituent, but this solid residue may contain appreciable amounts of sulfur, hydrogen, nitrogen and oxygen. Fixed carbon is obtained by subtracting the percent moisture, volatile matter and ash from 100% (Fryer 1974, Graboski 1979, Ode 1963).

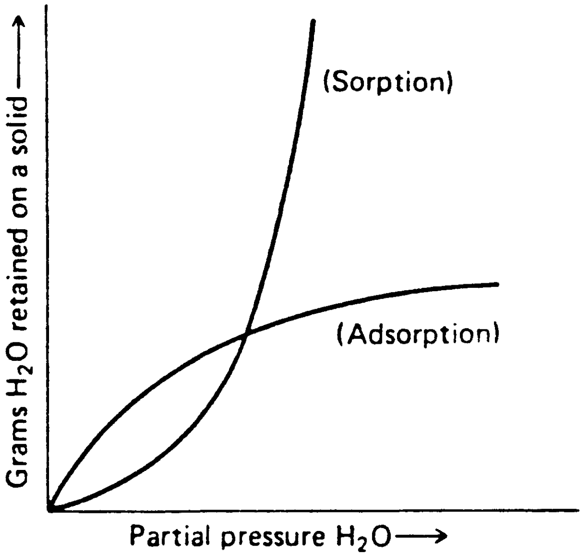
2.1.3 Moisture

In chemical terms the two forms of water are essential(bound) and nonessential(free). Essential water forms an integral part of the molecule or crystal structure of a component of the solid, for example as with the characteristic coal mineral Kaolinite($Al_2O_3-2SiO_2-2H_2O$) It occurs in stoichiometric proportions with other elements in a compound. Nonessential water is not stoichiometric and is retained by the solid as a consequence of physical forces.

Adsorbed water is retained on the surface of solids. Sorbed water is held as a condensed phase in the interstices or capillaries of collodial solids, like starch, protein, charcoal, zeolite or minerals. The anount of absorbed water on the surface of a solid increases with moisture content of the enviromment. Figure 1 shows adsorption is particulary sensitive to change in water vapor pressure at low partial pressures. The amount of adsorbed water approaches zero if the solid is dried at temperatures above 100 ^{o}C. The quantity of moisture sorbed by a colloidal solid varies tremendously with atmosphere conditions, as is seen in Figure 1. The amount of water retained by adsorption will involve quantities of water of

Figure 1

Adsorption and Sorption Isotherms



a few tenths of a percent of the solid, while sorption may entail 10 to 20 percent. Water sorbed in a solid decreases as temperature increases (see Figure 2), though complete removal is not usually accomplished at 100 °C.

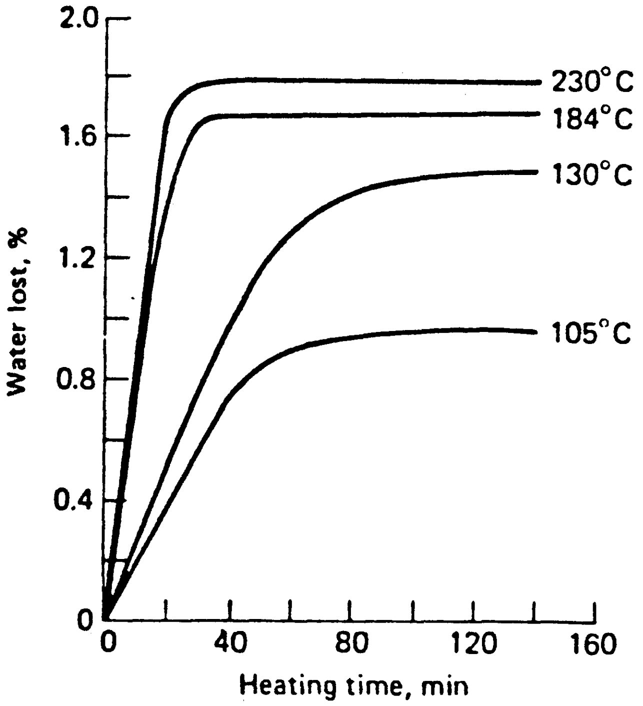
Occluded water is liquid water entrapped in microscopic pockets spaced throughout solid crystals, usually occuring in minerals and rocks. Occulded water is not in equilibrium with the atmosphere and is therefore insensitive to changes in humidity. Heating can cause diffusive loss of water but may also breakdown the crystals of the solid through steam pressure (Skoog 1976). Since moisture content is derived from a variety of sources and varies under environmental conditions, much of the data are reported on a dry basis or dry-ash-free basis.

2.1.4 Ultimate Analysis (ASTM D3178-73 (1983))

The ultimate analysis is used to characterize coals and biomass fuels in terms of carbon, hydrogen, oxygen, nitrogen, sulfur and ash content. Biomass is typically low in nitrogen, sulfur and chlorine (rarely greater than one percent). The amount of oxygen (or in older literature, oxygen and nitrogen) is always determined by subtracting the percentage of of carbon, hydrogen and ash from 100 percent. This method has the disadvantage of making the

Figure 2

Removal of Sorbed Water at Constant Temperature



reported percentage of oxygen subject to the cumulative error of all direct determinations and leads to an artificially balanced summation (Haslam 1926, Volborth 1979).

2.1.5 Heating Value (Parr Calorimeter Procedure)

Heat content is normally measured with a calorimeter. A sample is combusted in excess oxygen under pressure and the heat released is determined by measuring the change in temperature of water surrounding the bomb. (Hayes 1973, Sehgal 1974). The heating value number obtained with a bomb calorimeter is the gross or higher heating value, because the latent heat of the combustion water is recovered from the water produced as a result of condensation. Therefore, the value obtained is higher than it would be in under burning conditions. Normally, in power plant operations or in gasification, the water produced would escape as steam and its latent heat is not utilized (Sehgal 1974, Graboski 1979).

2.1.6 Elemental Analysis (ASTM D3682-78(1983))

Elemental analysis provides a quantitative analysis of the minerals in ash produced by combustion of coal or biomass. Table 3 shows the major inorganic constituents in coal ash. The elements determined in the ASTM (American Society for Testing and Materials) are Si, Al, Fe, Ca, Mg, Na, K, P, Ti, S and Mn and are reported in weight percent as oxides. The ash obtained differs from the mineral matter in the coal or biomass as most of the inorganic constituents are converted to oxide forms during ashing.

2.1.7 Ash Fusion Temperature (D1857-68 (1983))

Ash fusibility measures the temperature at which ash softens and becomes fluid when heated under prescribed conditions. Four temperatures are obtained in the ash fusion test; these are the initial deformation temperature, the softening temperature, the hemispherical temperature and the fluid temperature (see Figure 3). These temperatures are a function of the ash composition. A pure substance has a distinct melting point at one temperature versus a mixture of compounds which will melt over a temperature range. In the test, the sample is heated in a specified atmosphere, either reducing or oxidizing. The atmosphere affects what value is obtained for the fusion temperature. Iron, a common element in coal, has two

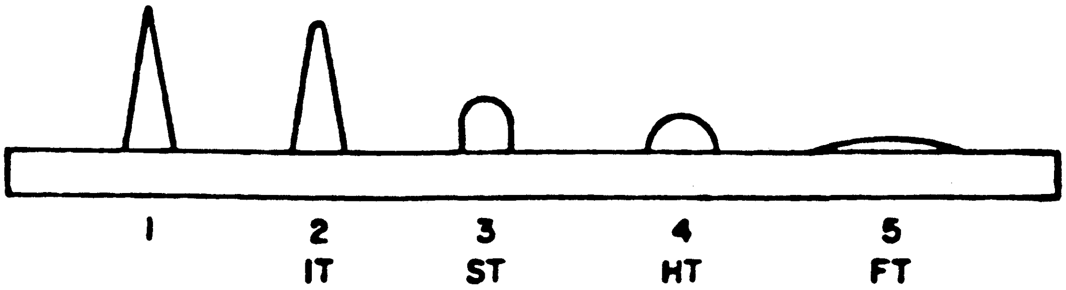
Table 3

Major Inorganic Constituents in Coal Ash

Constituents	Usual Percentage
SiO_2	50 - 90
Al_2O_3	50 - 90
Fe_2O_3	0 - 20
CaO	0 - 20
MgO	0 - 8
Na_2O	0 - 6
K_2O	0 - 6
SO_3	0.5 - 10
P_2O_5	0 - 1
TiO_2	0 - 2
Others	-------

Figure 3

ASTM Cone Shapes at Deformation Temperatures



1) Cone before heating

2) IT = Initial Deformation Temperature

3) ST = Softening Temperature

4) HT = Hemispherical Temperature

5) FT = Fluid Temperature

oxidation states, Fe^{+2} and Fe^{+3}. Many ashes show higher values of fusion temperatures under oxidizing conditions than reducing conditions due to the different flux effect of ferric and ferrous compounds (Sehgal 1974). Figure 4 illustrates this phenomenon for Wyoming sub-bituminous coal ash (Bryers 1976). Correlations between ash fusibility and the behavior of ash particles in actual operation is difficult, because of the disparity in conditions between finely ground, well mixed test samples in the laboratory and the indeterminate effects of segregation in a fuel bed. The simplicity of this test and lack of other standard testing methods makes it one of the most important tests in determining the fusion characterisitics of coal ash (Corey 1962, Sehgal 1974, Singh 1980, Sanyal 1981).

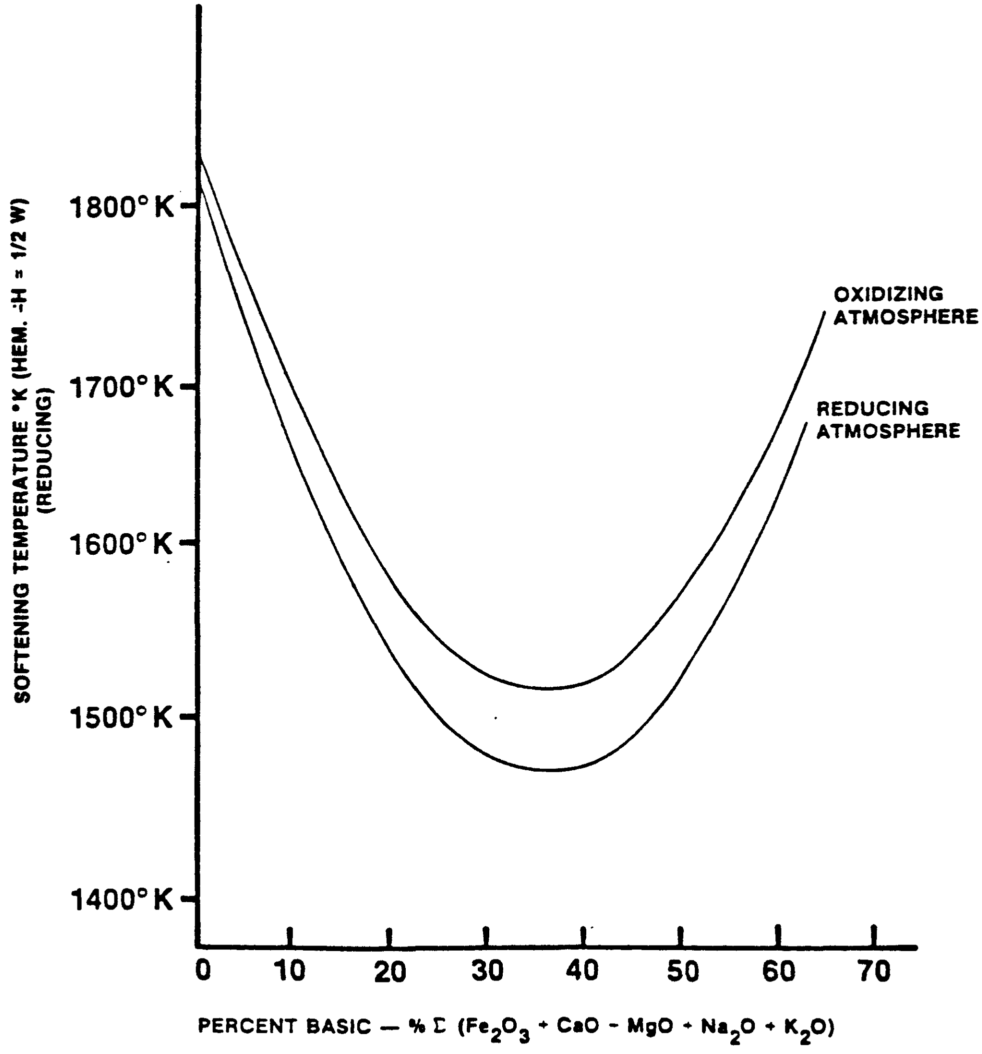
2.2 Coal Correlations

2.2.1 Heating Value

Mathematical correlations for higher heating values of coals have been proposed. Generally, these involve information about the chemical compostion, such as ultimate analysis or elemental analysis. Graboski and Bain (1979) showed that the Institute of Gas Technology's equation for higher heating value of coals gave the best estimate for

Figure 4

Comparison of Hemispherical Temperatures
under
Reducing and Oxidizing Atmospheres
for
Various Percentages of Basic Constituents
in Wyoming Sub-Bituminous Coal Ash



solid biomass fuels. This equation was developed using the experimental heating values and ultimate analyses of 700 coal samples. Using the data in the ultimate analysis, the IGT equation predicts higher heating values. Graboski and Bain (1979) found the IGT equation estimate gave an average error of +/- 150 BTU/lbm for biomass chars and fresh biomass.

$$HHV = 146.58*C + 568.78*H + 29.45*S - 6.58*A - 51.53*(O+N)$$

HHV in $\frac{BTU}{lbm}$.

All values on a dry weight percent basis.

C = Carbon
H = Hydrogen
S = Sulfur
A = Ash
O = Oxygen
N = Nitrogen

The IGT equation appears to provide a means of quantitatively evaluating the accuracy of the ultimate analysis.

2.2.2 Ash Fusion

Sage and McIlroy (1960) introduced a correlation ratio for predicting the temperature of 250 poise viscosity for melted coal ash. The constituents of coal ash are classed as either basic or acidic. The acidic components are silica, alumina and titania. The basic components are iron, the refractory components - calcium and magnesium, and the fluxing components - sodium and potassium. The correlation introduced was the base-to-acid ratio.

$$\frac{Fe_2O_3 + CaO + MgO + Na_2O + K_2O}{SiO_2 + Al_2O_3 + TiO_2}$$

Duzy (1965) stated that the term lignite-type ash is defined as an ash having more CaO plus MgO than Fe_2O_3. Coals having lignite-type ash include all those of the Jurassic Age and younger coals, such as coal from Alaska and the western United States. Nonlignite type ash has more Fe_2O_3 than CaO plus MgO and is typical of high rank coal comparable to that found in the eastern part of the United States and Great Britain. On this basis, cellulose type fuel such as wood, bark waste or bagasse have lignite-type ash.

The Bureau of Mines devised the silica ratio which gives a good correlation of the ash viscosity in the liquid range to the silica content in the ash.

$$\frac{100 * SiO_2}{SiO_2 + Fe_2O_3 + CaO + MgO}$$

Duzy introduced the dolomite ratio:

$$\frac{(CaO + MgO) * 100}{CaO + MgO + Fe_2O_3 + Na_2O + K_2O}$$

He found that both the silica ratio and the dolomite ratio appeared to have some correlation with the hemispherical softening temperature. Figure 5 shows that the ash fusibility increases with decreasing silica ratios. Similiarly, the ash fusiblity increases with increasing dolomite ratios, Figure 6.

Sondreal and Ellman (1975) studied the fusibility of ash from lignite coals and its correlation with ash composition. Lignite ash has higher proportions of Ca, Mg and Na than bituminous ash. Correlations for lignite ash developed by Sondreal and Ellman using statistical regression on elemental analyses of 680 samples of coal ash. The report presented equations which relate the ASTM (American Society for Testing and Materials) softening temperature to the ash analysis for a large and representitive group of lignite samples. Data included 338 analyses of ash from naturally occurring lignite, 279 analyses of ash from lignite modified by direct addition of mineral substances, 55 analyses of ash from lignite modified by ion exchange and 135 analyses of ash from bituminous coals.

Their report is split into three parts. In part one,

Figure 5

Silica Ratio and Dolomite Ratio of Ash
versus
Ash Fusibility

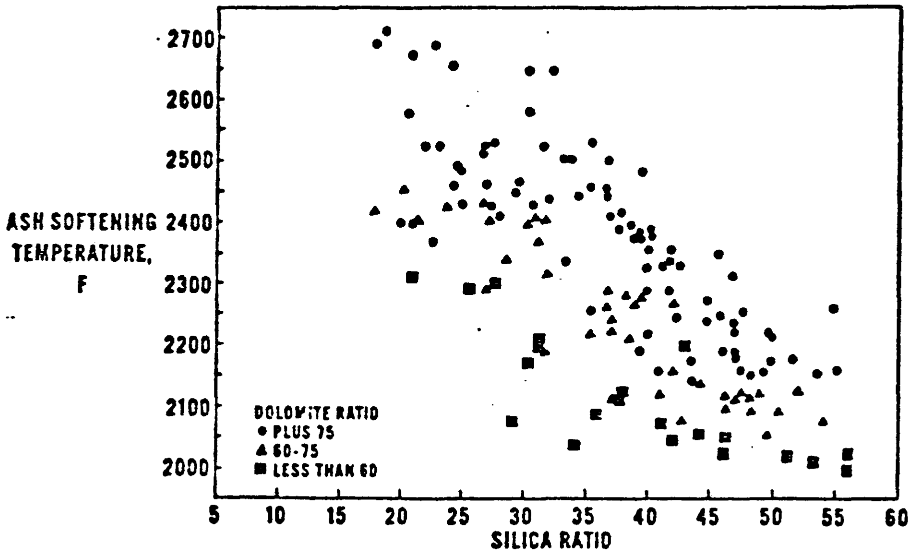
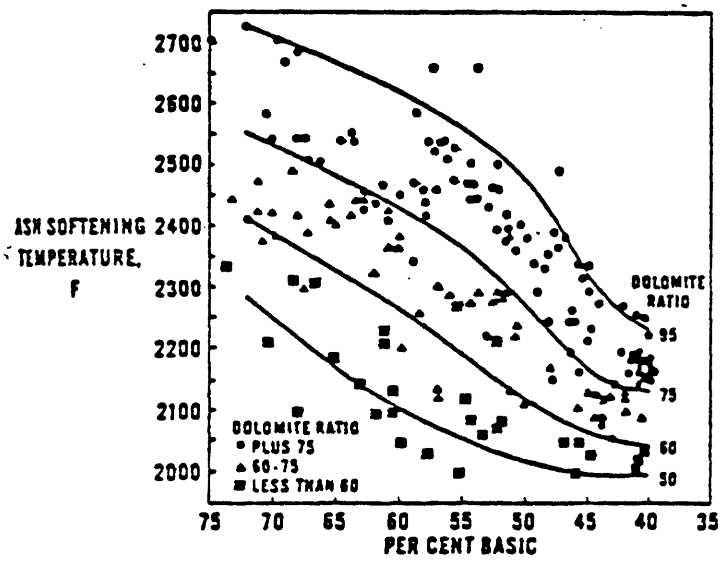


Figure 6

Basic Content and Dolomite Ratio of Ash versus Ash Fusibility



three recommended equations were given for predicting the softening temperature of natural lignite ash, ash from lignite modified by the addition of minerals and ash from lignite or bituminous coals. In part two, the effects of individual ash oxides on ash fusibility were given. Part three gave details on the progressive steps taken in the study, starting with the attempts to modify established indexes for application to lignite ash and proceeding to the statistical methods utilized in developing the equations given in parts 1 and 2.

Initially correlations for the softening temperature of lignite ash consisted of evaluating indices (ratios of various ash constituents) suggested previously by other investigators (Duzy, Sage & McIlroy, etc.). Attempts to develop an improved ratio progressed by utilizing linear multiple regression methods for relating ash constituents to ash softening temperature. The linear regression technique is a mathematical search to establish from the data the best linear mathematical expression which describes the relationship between a dependent variable and one or more independent variables. This study first related the softening temperature to the percentage of individual oxide components in the ash and progressed to more complex linear equations.

Table 4 contains the equation for pedicting ash

Table 4

Equation for Predicting the Ash Softening Temperatures for Natural Lignites

(1) Component	(2) Percent of ash	(3) Coefficient	(4) Product of columns 2 and 3
SiO_2	______	-3.725	- ______
Fe_2O_3	______	+39.067	+ ______
CaO	______	+93.634	+ ______
SiO_2 X Al_2O_3	______ X ______	+.8155	+ ______
SiO_2 X CaO	______ X ______	-.2214	- ______
SiO_2 X Na_2O	______ X ______	-.0975	- ______
SiO_2 X SO_3	______ X ______	-.4880	- ______
Al_2O_3 X CaO	______ X ______	-.8674	- ______
Fe_2O_3 X CaO	______ X ______	-2.4234	- ______
Fe_2O_3 X MgO	______ X ______	+2.0770	+ ______
CaO^2	______ X ______	-.8765	- ______
MgO X Na_2O	______ X ______	-1.3431	- ______
SO_3^2	______ X ______	+.0764	+ ______
Constant term			+ 1,027
Calculated softening temperature (sum of column 4)			= ° F

R is 0.875 and SE is 83.8° F.

softening temperature for 338 natural lignites. Table 5 is the equation for predicting ash softening temperatures of lignites supplemented by additives, using 338 analyses for natural lignite ash plus 279 analyses of modified samples. Table 6 is the equation for predicting ash softening temperatures of bituminous and lignite coals, using 338 samples of ash from natural lignite and 135 ashes from bituminous coals. This equation uses two parameters proposed by Duzy (1965); the fraction of basic constituents (Fe_2O_3, CaO, MgO, Na_2O, K_2O) and the dolomite ratio. In Table 4, 5 & 6, R is the correlation coefficient; the value zero indicates no correlation (complete randomness) and the values one or minus one indicate a perfect correlation (exact agreement between data and prediction). SE is the standard error of estimate, which is the range that 68 percent of the computed values will fall, assuming a normal distribution.

Winegartner and Rhodes (1975) employed a stepwise multivariable regression program on a database of 1212 coal ash samples (626 midwestern coals and 586 western coals) in an attempt to relate their compostion to ash fusion temperatures. The major objectives of this study were to develop a technique for calculating ash fusion temperatures from the chemical compostion of coal ash, to provide a method for calculating the ash fusion properties of coal

Table 5

Equation for Predicting Ash Softening Temperatures of Lignite Supplemented by Additives

(1) Component	(2) Percent of ash	(3) Coefficient	(4) Product of columns 2 and 3
SiO_2	____	-9.666	- ____
Al_2O_3	____	-17.209	- ____
Fe_2O_3	____	+18.441	+ ____
TiO_2	____	+6.423	+ ____
P_2O_5	____	-14.262	- ____
CaO	____	+35.281	+ ____
MgO	____	+23.544	+ ____
Na_2O	____	+7.545	+ ____
SO_2^2	____ x ____	+.1467	+ ____
SiO_2 x Al_2O_3	____ x ____	+.2898	+ ____
SiO_2 x Na_2O	____ x ____	-.1984	- ____
SiO_2 x SO_3	____ x ____	-.2839	- ____
$Al_2O_3^2$	____ x ____	+.6223	+ ____
Fe_2O_3 x CaO	____ x ____	-.8671	- ____
$P_2O_5^2$	____ x ____	+.4531	+ ____
CaO^2	____ x ____	-.3142	- ____
CaO x SO_3	____ x ____	+.2331	+ ____
MgO x Na_2O	____ x ____	-.9299	- ____
Constant term			+ 1,654
Calculated softening temperature (sum of column 4)			= ☐ ° F

R is 0.856, and SE is 86.8° F.

Table 6

Equation for Predicting Ash Softening Temperatures of Bituminous and Lignite Coals

A. CALCULATION OF BASIC CONSTITUENT RATIO (BC)

Component			Component		
Fe_2O_3		______	Numerator		______
CaO	+	______	SiO_2	+	______
MgO	+	______	Al_2O_3	+	______
Na_2O	+	______	TiO_2	+	______
K_2O	+	______			
Numerator	=	______	Denominator	=	______

Basic constituents (BC) = $\frac{\text{Numerator}}{\text{Denominator}}$ ______ = ☐

B. CALCULATION OF DOLOMITE RATIO (DR)

Component			Component		
CaO	+	______	Numerator		______
MgO	+	______	Fe_2O_3	+	______
Numerator	=	______	Na_2O	+	______
			K_2O	+	______
			Denominator	=	______

Dolomite ratio (DR) = $\frac{\text{Numerator}}{\text{Denominator}}$ ______ = ☐

C. SOFTENING TEMPERATURE

Term		Coefficient		Product
BC	______	-3,631.0	-	______
BC^2	______ X ______	+2,993.3	+	______
DR	______	-1,456.5	-	______
DR^2	______ X ______	+1,022.1	+	______
BC X DR	______ X ______	+1,558.7	+	______
Constant term			+	3,238
Calculated softening temperature (sum of product column)			=	☐ °F

R is 0.812, and SE is 105.8° F.

blends and to develop an improved understanding of effect, significance and interaction of ash elements with respect to the thermal properties of coal ash. Fifty-one properties or independent variables were used in the final regression analyses. They included all the basic correlations commonly found in the literature. They used the stepwise regression program from the UCLA Biomedical Computers Programs. It derived an equation of the form:

$$y = \text{constant} + aX_1 + bX_2 + cX_3 + dX_4 \ldots.$$

where y was a property of one of the ash fusion temperatures and X_1, X_2, etc. were chemical properties such as % CaO, % SiO_2, % SiO_2 * % SiO_2, etc. Standard error of estimate, SE, and reliability of calculated values, R, are given.

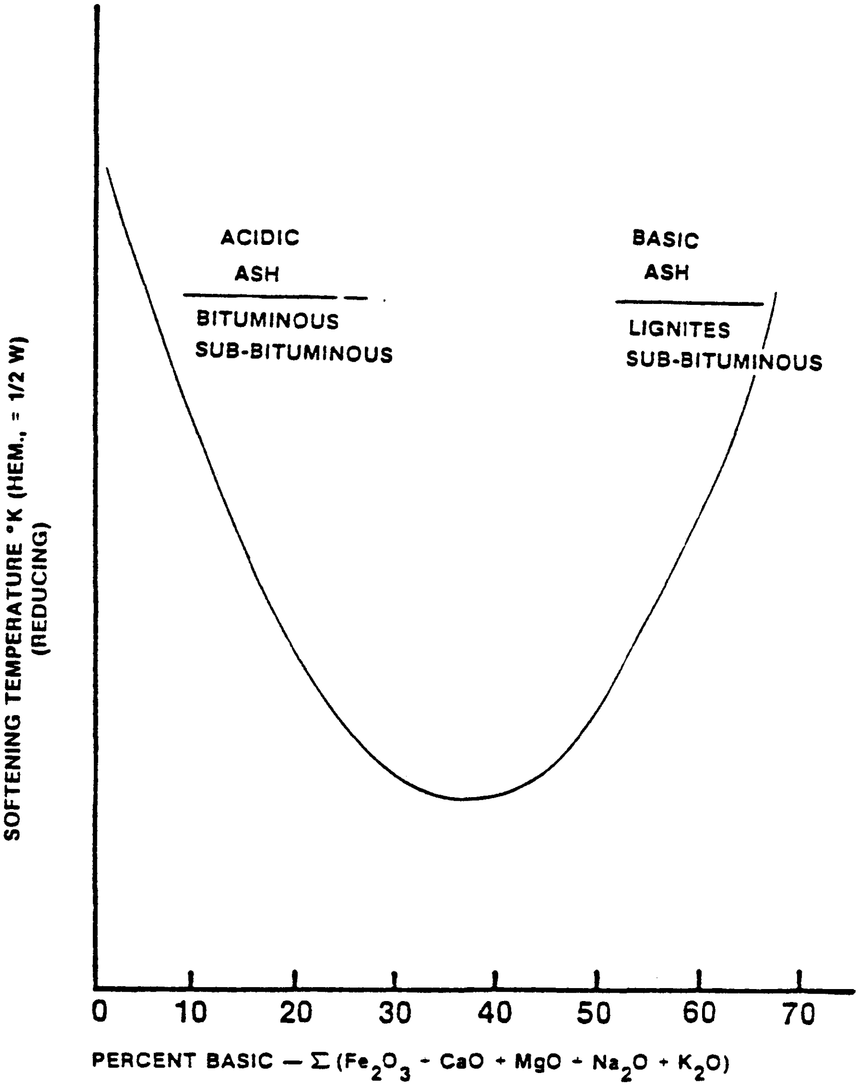
Winegartner and Rhodes stated that mole percent should be used instead of weight percent for an element. The computer continually derived coefficients of the independent variables in even multiples of the molecular weights of the oxides. Mole percent was calculated by dividing the weight percent by the moelcular weight and normalizing. They reported iron as FeO instead of Fe_2O_3. Winegartner and Rhodes stated the SO_3 content of the ash was a function of how the coal was burned in a laboratory setting and had little relationship to the SO_3 content of the furnace ash; therefore SO_3 was left out of the ash composition.

The samples were separated into three groups in the Winegartner and Rhodes study: Eastern and Western coals combined (1212 samples), Eastern coals only (626 samples) or Western coals only (586 samples). They reported eight ash fusion temperatures for each group, the initial deformation temperature, softening temperature, hemispherical temperature and fluid temperature for reducing and oxidizing conditions. Six other values were calculated; the difference of the fluid temperature minus initial deformation temperature for reducing and oxidizing conditions and the difference between oxidizing minus reducing for the four ash fusion temperatures.

Bryers and Taylor (1976) performed a stepwise second order multiple regression analysis using individual basic constituents as the independent variable on Eastern and Western coals. Figure 7 shows the relationship of percent basic constituents on hemispherical temperature. The expression developed provided a very good fit to the data. Bryers and Taylor decided it was too cumbersome to handle. Rather than fit the data with a good deal of precision, they returned to a single variable second order regression analysis and used percent basic constituents as the independent variable. The equations were derived for

Figure 7

Hemispherical Temperatures in Reducing Atmosphere versus Percent Basic Constituents in Ash



lignite and Wyoming sub-bituminous coals with an SiO_2/Al_2O_3 ratio greater than one, Wyoming sub-bituminous coals with a SiO_2/Al_2O_3 ratio greater than one, Wyoming sub-bituminous coals with a SiO_2/Al_2O_3 ratio approximately equal to one and eastern bituminous coals. Table 7 contains the three equations based on Western and lignite coals developed by Bryers and Taylor. Figure 8 shows the relationship of the basic constistuents of the various coals on hemispherical temperature.

2.3 Actual Biomass Use

Most biomass available is a waste product from some process. Sunflower shells or walnut shells are wastes from food oil production or nut extractions. Sawdust and bark are wastes from lumber and paper production. Straws are left after grain harvesting. They all cause disposal problems and burning the material, as a means of disposal, causes pollution problems (Horsfield & Williams 1978). Some companies are actually utilizing their wastes to recover some of the available energy to power their process (Reason 1983).

Table 7

Bryers Equations for Hemispherical Temperatures for Western Coals under Reducing Conditions

1) Lignites + Wyoming Coals: $SiO_2/Al_2O_3 >> 1$

$$H.T. = 2863 - 37.1x + 0.51x^2$$

R = .772 SE = 100.4 Data Points = 151

2) Wyoming Coals: $SiO_2/Al_2O_3 >> 1$

$$H.T. = 2814 - 35x + 0.50x^2$$

R = .773 SE = 99.5 Data Points = 79

3) Wyoming Coals: $SiO_2/Al_2O_3 \sim 1$

$$H.T. = 2992 - 27.1x + 0.27x^2$$

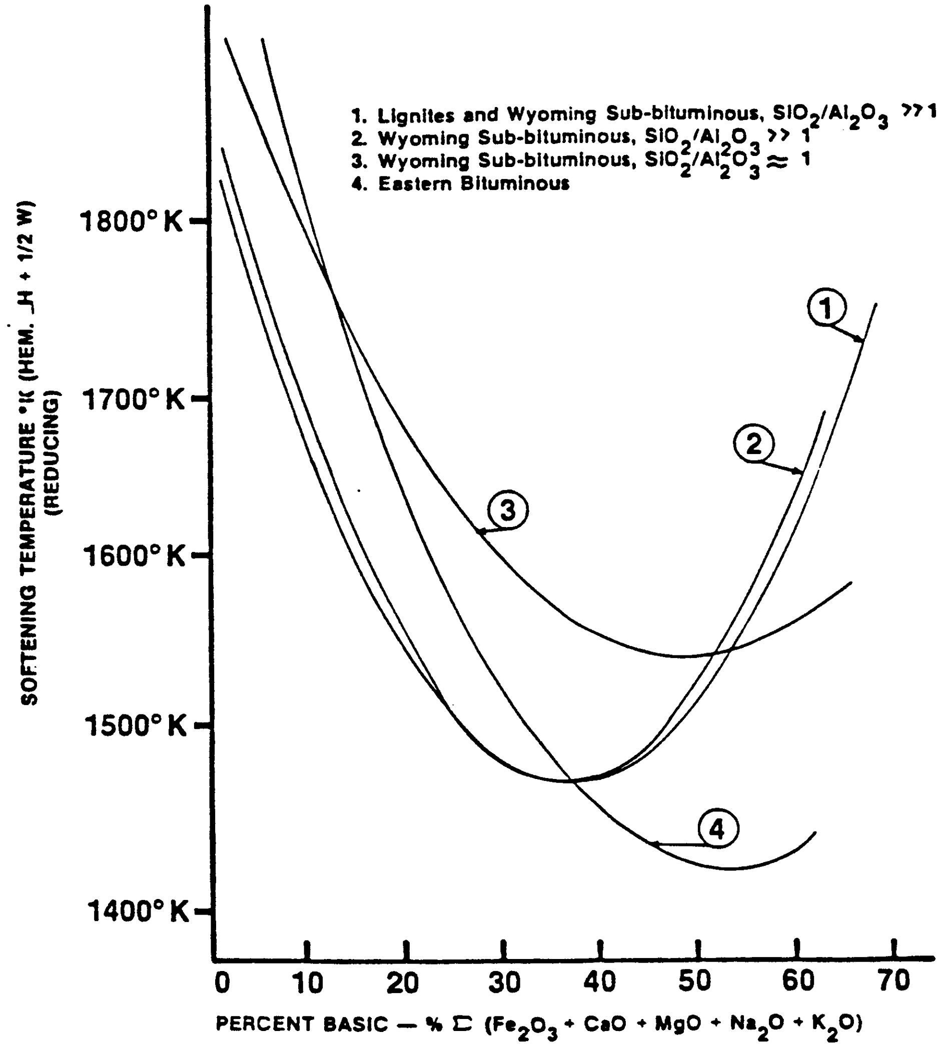
R = .63 SE = 113.1 Data Points = 50

x = Basic Constituents

H.T. = Hemispherical Temperature in degrees Fahrenheit

Figure 8

The Influence of Percent Basic Constituents in the Ash on Ash Hemispherical Temperatures Under Reducing Conditions for Different Ranks of Coal



2.3.1 Laboratory Gasification Studies on Biomass Fuels

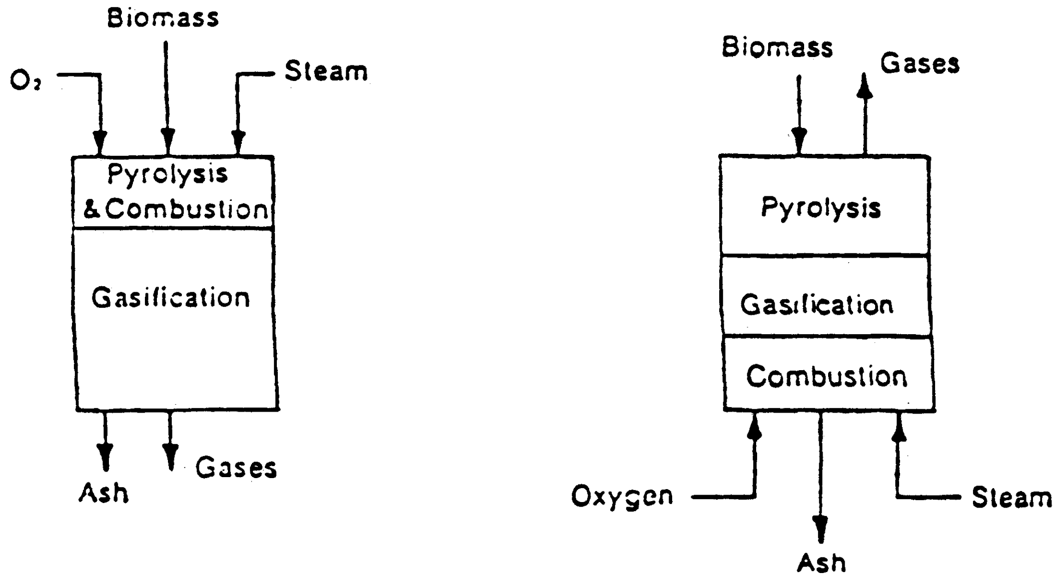
Woods and agricultural wastes are low grade energy sources with heating values from 6000 to 9500 BTU/lbm. For successful utilization of this energy at the lumber, farm or food processing level, a simple, low cost method of converting biomass to heat or shaft horsepower is needed. Gasification is an energy conversion method which could be run solely with these residues (Horsfield 1978).

Cruz (1977) explored the use of agricultural wastes in updraft and downdraft gasifiers. Coconut shells and woods were the fuels used. The coconut shells exhibited clinker formation in the updraft configuration. The clinker formation was negligible when the coconut shells fuelled a downdraft gas producer.

Williams and Horsfield (1977) stated downdraft gasifiers were better suited to handle agricultural wastes than updraft. In updraft gas producers, (Figure 9) the hot gases flow counter to the fuel. Pyrolysis occurs in the low temperature area of the gasifier and the resulting gas stream has a high tar content. Agricultural wastes and other biomass fuels are characterized by high volatiles content. Downdraft producers have the potential to eliminate tar from the product gas. The pyrolysis products must pass through the reaction zone, where they are broken

Figure 9

Modes of Fixed Bed Gasifer Operation



Downdraft

Updraft

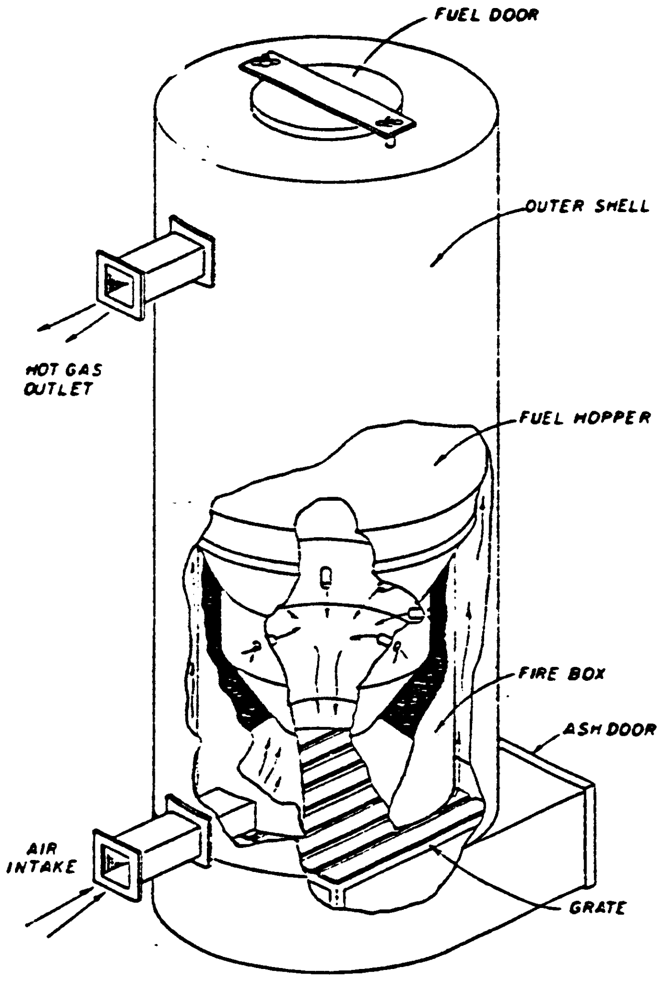
down, before combining with exiting gases (Figure 9).

The gas produced from the gasifier used by Williams and Horsfield (1977) was used to fuel a Wisconsin V460D engine or a 10 kW engine-generator. Engine performance was studied while running on producer gas generated from different agricultural residues (walnut shells, tree prunings, rice hulls, alfalfa cubes, cotton gin waste and corn cobs). Wood chips bridged in the hopper which fed material to the gasifier causing stoppage of the process. A stirrer in the hopper did not help. The nut shells and rice hulls fed well into the gasifier. The rice hulls were high in ash content (20%) and had to be fed fast to keep the gasifier full of fuel. The nut shells were high in tar content and clogged the filter. They also tended to fluidize, causing air flow problems. Corn cobs caused clinkers at the grate, which impeded the flow of air through the reaction zone. An eccentric rotating grate was added which crushed the clinkers, alleviating the problem.

In more recent articles by Williams and associates (1978, 1979), the grate configuration was stressed. The grate is a metal framework that supports the fuel bed, which enables the solid refuse (ash and char) to be continuously removed from the bottom of the bed and provides unhindered passage for the exiting producer gas (see Figure 10). At times it must provide suitable bed

Figure 10

Laboratory Gasifier with Grate



agitation. The eccentric grate worked well with the larger particles and fuels that clinkered (Figure 11). It did not support granular fuels (mulled walnut shells) because the fuel was displaced too rapidly and extinguished gasification reactions. A perforated basket grate with a wiper worked well with these fuels (Figure 12).

Williams (1978) states that ash fusion temperatures of inorganic matter determines formation of clinkers in the oxidation zone. The ash components form eutectic mixtures of a lowest melting point which melt out from the whole mass. The cotton gin waste was particularly prone to clinkering and was screened to remove fine organic matter. Curley et al (1978) addressed this problem and found that cotton gin waste ash slagging problem was due to silica in the soil material associated with the residue. Screening resulted in a compromise between eliminating soil and saving as mucn combustible material as possible. The quantity of slag was reduced after screening. Williams (1978) also noted that total ash content is important, as it is often present at expense of carbon.

Williams and Goss (1979) discussed waste gasification characteristics. The rice hulls had a high ash content and low bulk density. They were susceptible to fluidization and the hulls got entrained in the exiting gas. They were pelletized to improve feeding into the gasifier. The

Figure 11

Laboratory Gasifier with Eccentric Grate

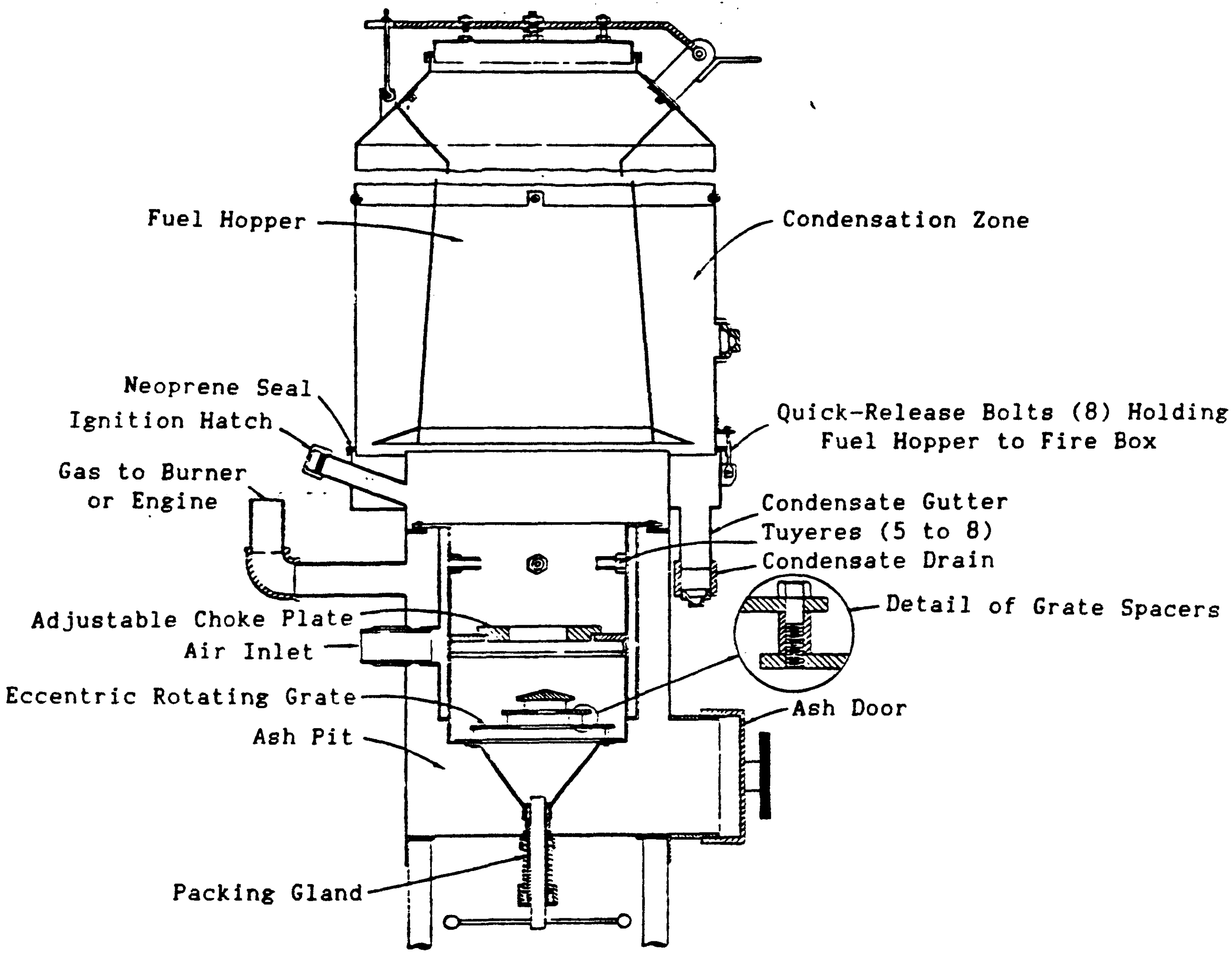
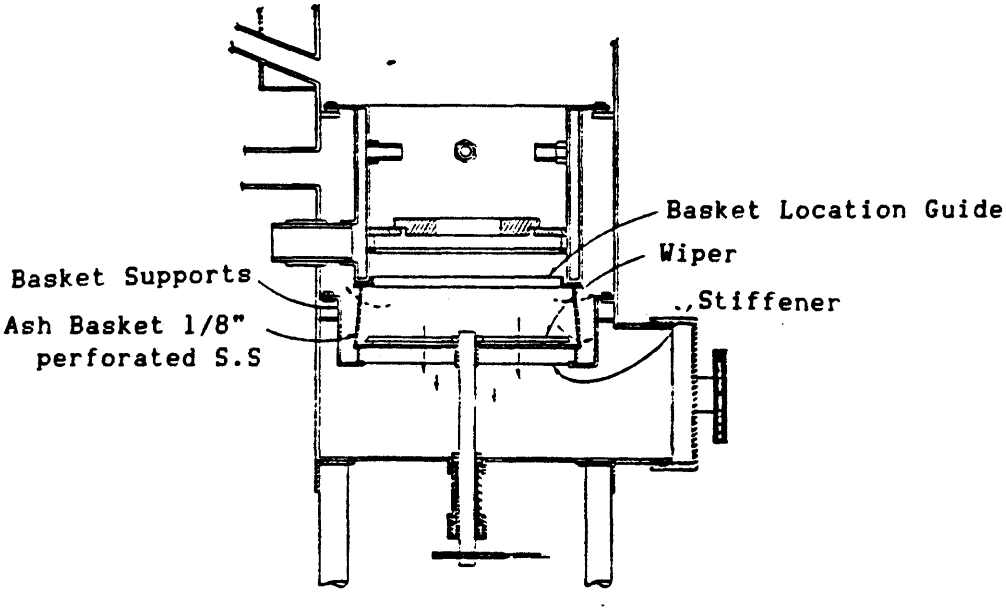


Figure 12

Basket Grate with Wiper



producer gas resulted in low yields of low quality gas. Wood chips produced good yields of generator gas. Williams and Goss found wood chips and corn cobs were ideal for gasification due to high heating value, low ash content and suitable size. Walnut shells produced a gas of high heating value at a high yield. Due to the granular nature of the walnut shells, a special grate was required. Cotton gin trash produced low heating value gas and required pretreatment before gasification. The cotton gin trash bridged in the hopper and had a high ash content due to inorganic impurities.

Jenkins (1980) ran a laboratory scale, fixed bed, air blown, downdraft gas producer using agricultural and forest residues and municipal wastes. The ash content of the fuels tested ranged from 0.1% to 17.6%. The ash content decreased the energy density and inhibited the gasification process through formation of large amounts of slag in the firebox. Firebox obstruction limited the fuel flow and shifted the air to fuel ratio towards combustion. This shift to combustion decreased the gas quality, increased the reaction temperature and stressed internal parts of the producer.

The degree of slagging depended on the amount of mineral matter present and the composition of the mineral matter. Table 8 is a list of the fuels used in the

Table 8

Degree of Slagging in Fuels Used by Jenkins (1980)

Slagging Fuels	% Ash	Degree of Slagging	Non-Slagging Fuels	% ash
Barley straw mix	10.3	Severe	Cubed alfalfa seed straw	6.0
Bean straw	10.2	Severe	Almond shell	4.8
Corn stalks	6.4	Moderate	Corn cobs	1.5
Cotton gin trash	17.6	Severe	Olive pits	3.2
Cubed cotton stalks	17.2	Severe	Peach pits	0.9
RDF pellets	10.4	Severe	Prune pits	0.5
Pelleted rice hulls	14.9	Severe	Walnut shell (cracked)	1.1
Safflower straw	6.0	Minor	Douglas Fir wood blocks	0.2
1/4" pelleted walnut shell mix	5.8	Moderate	Municipal tree prunings	3.0
Wheat straw & corn stalks	7.4	Severe	Hogged wood manufacturing residue	0.3
			Whole log wood chips	0.1

gasifier Jenkins operated, and their degree of slagging. Jenkins stated that the amount of ash present in the fuel influenced the degree of slagging. The ash content of the fuels which did not slag was below 6.0%, while the ash content of the slagging fuels was above 5.8%.

Ash composition effected the potential for slagging by providing the elements to form a eutectic mixture. Jenkins analyzed the cotton gin trash fuel and the resultant slag for metal content (Table 9). Though Ca and K were major elements in the fuel (39 % and 27.8 % respectively), the slag contained, in major amounts, Si (23.9 %), Ca (24.4 %) and K (29.5 %). Jenkins stated that a mixture of SiO_2, K_2O and CaO would have a melting point of 1350°C (2462°F) (Figure 13), a temperature easily achieved in the firebox.

2.3.2 Biomass Use in Industry

Garbeff (1981) reported on Sun-Diamond Growers of California's success with biomass energy conversion of walnut shells. Gasification effectively produced a clean, low-BTU gas. However, mechanical difficulties kept the equipment off-line too often to be commercially feasible. Garbeff states that the walnut shells were burned directly in a furnace and a co-generation system was set-up. This system provided virtually all the energy required for the

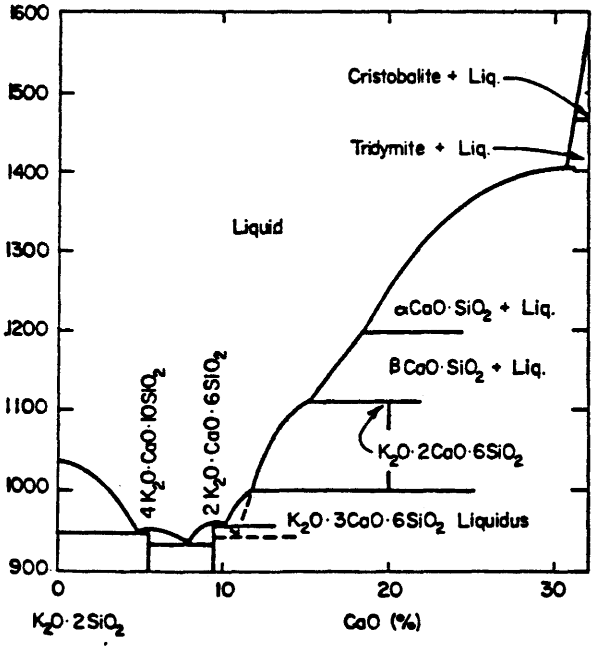
Table 9

Analyses of Metals in Cotton Gin Trash Fuel and Cotton Gin Trash Slag

	% of Total Metals Found	
Element	Fuel	Slag
Na	2.3	1.5
Mg	1.9	2.0
Al	0.9	3.4
Si	5.7	23.9
S	4.6	0.8
Cl	8.4	0.3
K	27.6	29.5
Ca	39.0	24.4
Ti	0.3	0.3
V	0.3	0.1
Cr	0.29	0.1
Mn	0.28	0.2
Fe	3.5	10.2
Ni	0.22	0.1
Cu	0.19	0.1
Zn	0.19	0.1
Br	0.47	0.3
Ba	1.1	0.4
Pb	0.9	0.5
P	1.6	2.0

Figure 13

Eutectic Diagram for the System K_2O-SiO_2-CaO (Levin 1974)



plant and is currently in use.

Brudenell and Holland (1981) reported on sunflower seed hulls used as a supplementary fuel for a coal-fired powerplant in Bismark, North Dakota operated by the Basin Electric Power Cooperative. Coal was the primary fuel and the fuel ratio of coal to sunflower seed hulls was 9:1 or 8:2. The preliminary combustion testing of the sunflower seed hulls was performed at the Grand Forks Energy Technical Center, North Dakota. Both Ness (1979) and Brudenell (1981), stated the high potassium content of sunflower hulls had the potential to be a fouling concern. Actual use at Bismark, proved that supplementing coal with does not increase ash and fouling problems.

Reason (1983) surveyed four utility companies utilizing biomass as a fuel. The Washington Water Power Co. at Kettle Falls was constructing a utility powerplant to be fired entirely by wood. The Lake Superior District Power Co., Wisconsin, has been supplementing coal with wood waste for a 92-MW powerplant (on the south shore of Lake Superior) since 1971. Original fuel consumption was estimated to be 30-40% wood, with a more recent ratio of 75% wood. The goal is to employ 100% wood waste with coal as the secondary fuel. Molokai Electric Co., Hawaii, fires their steam generator with a combination of straw, wood chips, pineapple waste and waste paper. Coal is available as a standby fuel. This powerplant has been on line since May 1982. Burlington Electric Dept. is constructing a 50-MW powerplant which is designed to use wood as the main fuel and coal as the secondary fuel. They have two 10-MW converted wood fired powerplant units at their Moran station in Burlington. These units have been successfully producing power at a cost 30% lower than the previous coal fired units.

3. EXPERIMENTAL PROCEDURE

3.1 Sampling

Sampling is a term used to describe the operations involved in procuring a reasonable amount of material that is representative of the whole. With biomass, this is a difficult process since one starts with a bulky particulate material that is not homogeneous. Repeated grinding, milling and dividing will provide a homogeneous sample with enough surface area for ready attack by reagents (Skoog 1976). Since excessive crushing or grinding can alter the composition of the sample, care should be taken to achieve the size reduction needed while maintaining sample integrity.

The agricultural wastes and the woods were prepared on an "as received" basis, in regards to moisture. Because of the varied size and type of the material, they were put through a small Wiley cutting mill, capable of reducing particles to about 20 mesh. Going to a smaller mesh caused many problems. Most of the material, due to moisture content, would gum up the cutting knifes before reaching a 40 mesh size. This also increased milling time by a factor of 3 to 4. The milling procedure, while making handling and testing simpler, increased sample uniformity problems.

When dealing with coals or ores, to reduce large volumes and maintain sample uniformity, the material is run through a series of riffle boxes. These systematically help reduce the volume without giving preference to any of the material. Most of the biomass samples came bailed, boxed or loose in large containers. Trying to choose sample material for size reduction while maintaining a good sample mix is difficult. Cotton gin waste is a good example; a proper percentage of sticks, cotton and boles must be milled to maintain sample uniformity.

The mixed hardwood, pine wee chips, S. Carolina tree chips and redwood sawdust arrived reduced in size. These samples allowed for easy mixing and milling, thus allowing for a high confidence of obtaining a representative sample. The two barks were cumbersome and required manual size reduction before they could fit into the mill. Also, the two redwoods and the fir bark were difficult to mill due to the higher moisture content which caused gumming up of material on the cutting knives, rendering them ineffectual.

The straws arrived bailed and loose. This material caused no problems with the mill. Manual riffling was used to split a representitive sample. The rice hulls and peanut hulls were small in size to start with, making milling easy and sample representation higher. Sugar cane bagasse is the fibrous residue left when sugar cane is milled (Lamb 1976). The bagasse was received as a fairly dry, stringy material not very large in size. All this made the milling easy and chances for choosing a uniform sample high. The corn cobs, cotton gin trash and walnut shells required manual size reduction. Cotton gin trash is a mixture of sticks, leftover cotton and the cotton pods (husks). Even after milling, this sample was not as well mixed as some of the other materials. The corn cobs and walnut shells milled easily after initial size reduction.

3.2 Proximate Analysis

The proximate analysis is based on the ASTM method D3172-73(1983) for coal and coke. The ground material is weighed into a nickel crucible and dried overnight at 105°C for moisture content. To devolatilize the sample, it is covered and placed in a Hoskins electric furnace at 900°C for 7 minutes. After cooling (in a desiccator) and weighing, the sample is ashed (uncovered) in a muffle furnace at 700-800°C for 4 hours. The woods ashed nicely at 800°C, but the agricultural wastes ashed at 800°C appeared to agglomerate. The agricultural waste ash turned out finer and fluffier at 700°C. Corn cob ash quality appeared to be a stronger function of temperature and was ashed at 700°C. The fixed carbon is calculated by subtracting the percentage of moisture, volatile matter and ash from 100%.

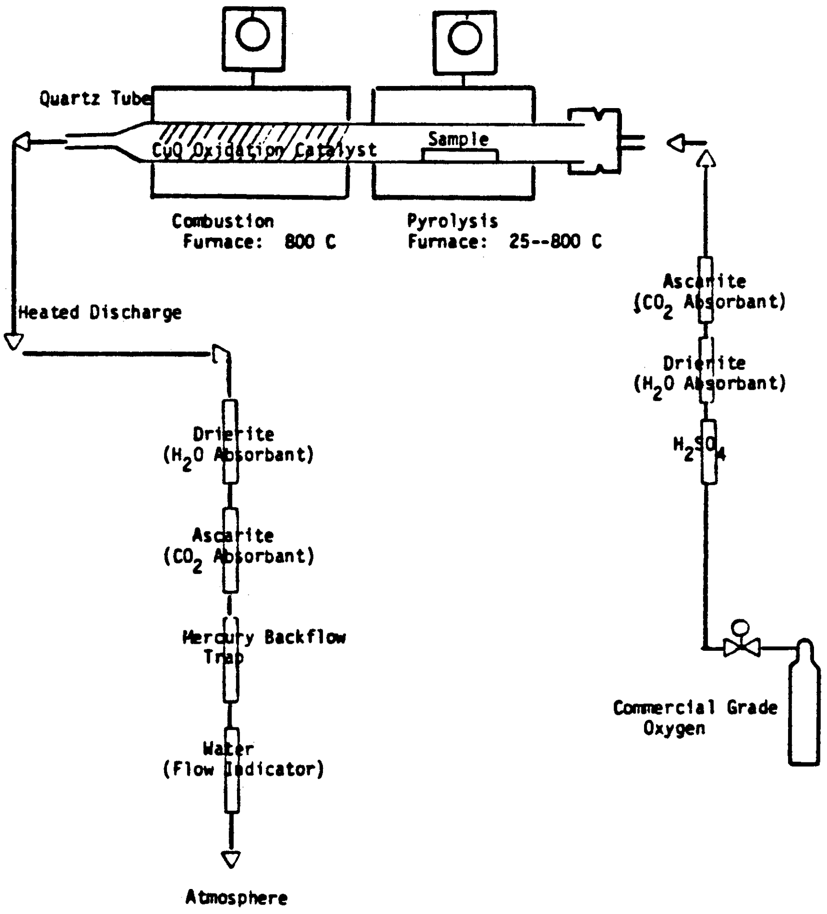
3.3 Ultimate Analysis

The ultimate analysis is based on the ASTM method D3178-73(1983) for coal and coke, and determines the carbon, hydrogen and oxygen content of a combustible material in an excess of oxygen. The apparatus for the analysis consisted of an oxygen purifying train, a pyrolysis furnace, a combustion furnace and an adsorption train to collect water and carbon dioxide (Figure 14). To ensure complete oxidation of the combustion products, cupric oxide is packed in the combustion section of the quartz tube. Lead chromate and silver gauze can be packed at the end of the tube to remove any interfering substances such as sulfur dioxide.

An oven dried (105°C) sample is weighed into a porcelain combustion boat. The sample is placed into the pyrolysis furnace section and the oxygen is turned on to 50-100 ml/min. The temperature of the furnace is raised from 25°C to 700-750°C in a four hour period at an incremental rate. The water vapor and carbon dioxide are collected on adsorbing materials, drierite and ascarite, respectively. The weight change of the adsorbers is

Figure 14

Ultimate Analysis Apparatus



measured and carbon and hydrogen can be calculated with respect to total sample weight, assuming negligible sulfur and nitrogen. The ash is weighed. The oxygen (plus sulfur, nitrogen and chlorine) is calculated by subtracting carbon, hydrogen and ash from the total sample weight. Better results and repeatability were obtained by using a finer mesh drierite (10-20 mesh) and ascarite (20-30 mesh) and by freshening these materials each run. Final temperature for the pyrolysis was kept to 700-750°C to prevent agglomeration of the agricultural wastes. Nitrogen, sulfur carbon and hydrogen were determined with a Carlo Erba elemental analyzer by the Colorado School of Mines Coal Laboratory. Chlorine was determined on the whole sample using nuetron activation analysis, courtesy of the United States Geological Survey in Denver, Colorado.

3.4 Higher Heating Value

The apparatus used for determining higher heating values was a Parr 1341 Plain Jacket Oxygen Bomb Calorimeter (Figure 15 & 16). The oven dried (105°C) sample is weighed into a container which is placed into a holder which goes in the bomb. The bomb is then pressurized with oxygen and placed in a stainless steel container of water which is inside a jacket housing. The cover for the jacket holds a

Figure 15

Plain Jacket Oxygen Bomb Calorimeter

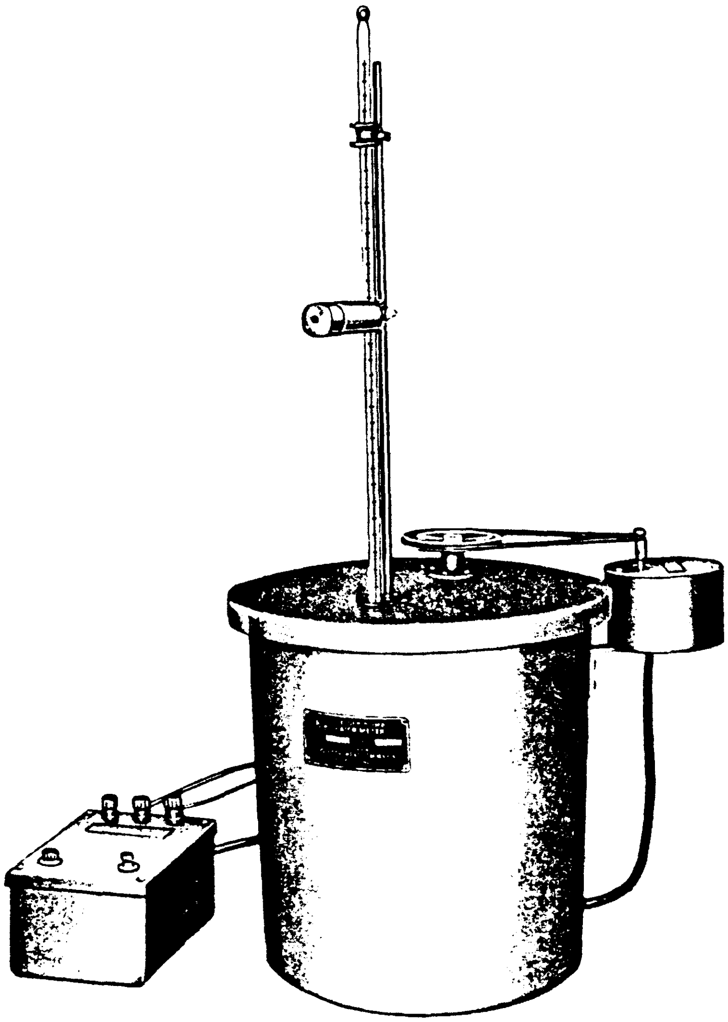
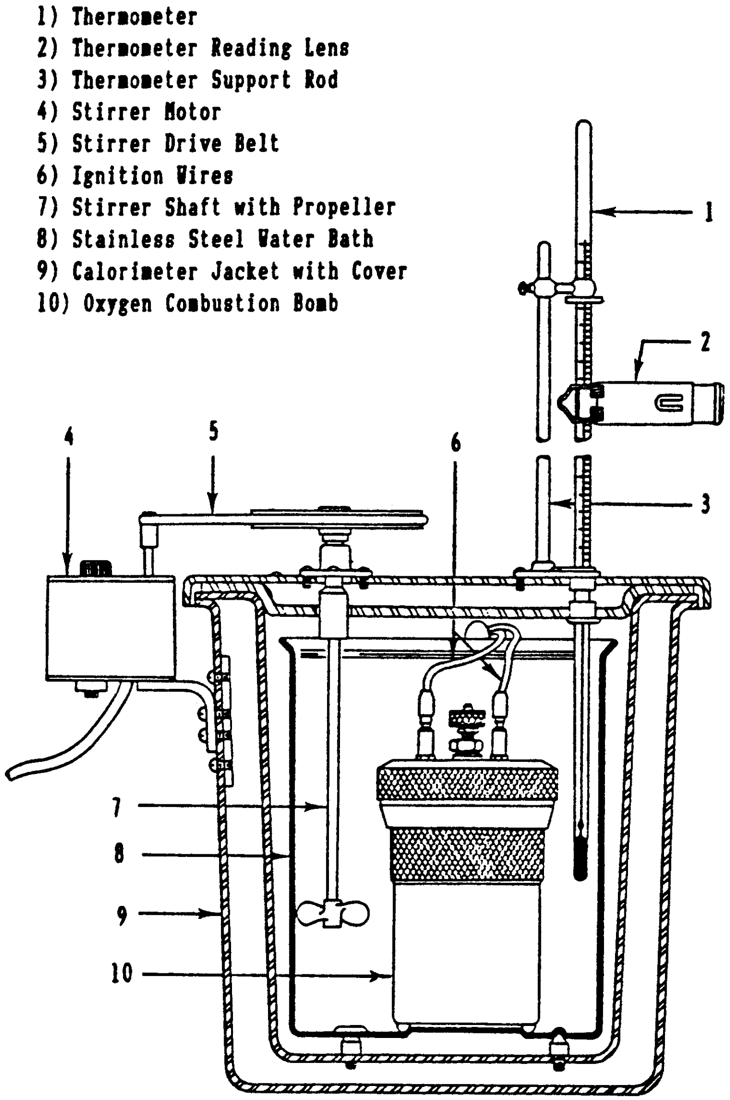


Figure 16

Schematic of Bomb Calorimeter



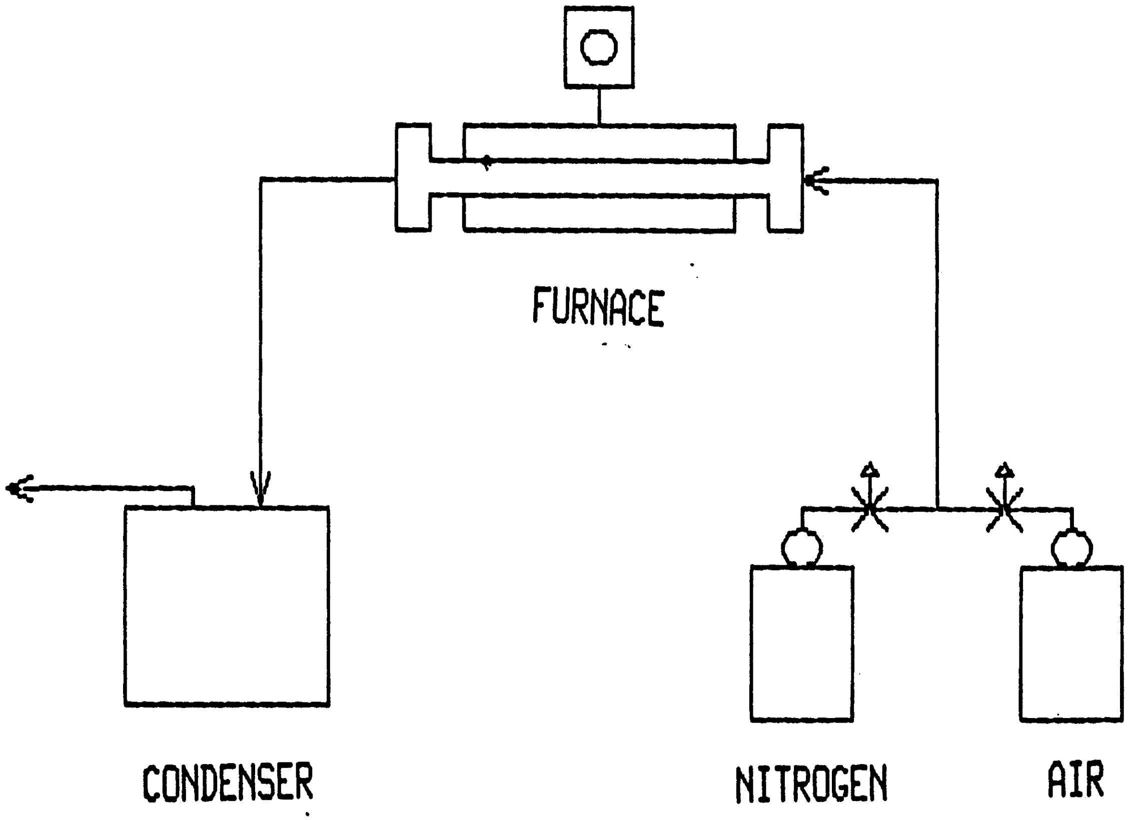
mixer for the water and the thermistor, which measures the temperature change in the water occuring from the temperature rise in the bomb, caused by combustion. Routine procedures require adding one ml of water to the bottom of the bomb for titration of sulfur. Since the samples in question are very low in sulfur (<1%), this was neglected. Usually a .5-1.5 g sample was weighed and hand pressed into the sample container. The hand pressing helped lower the occurrence of the lighter, fluffier material blowing out of the container upon ignition before combusting. Making sure the ignition wire was a little above the sample also helped.

3.5 Ashing

Since the majority of the inorganic matter in the samples is contained in the ash, ashing is a way of concentrating this matter for testing of the major and minor elements. The method used was a modified version stated in ASTM D3682-78(1983) for coal and coke. Compared to coals, the woods and agricultural wastes are lower in ash. Though the agricultural wastes are much higher in ash content (>1% - 20%) than the woods (<1%).

The first step involved charring the materials. A Lindberg electric furnace with a 1 1/2 inch i.d. by 4 foot long stainless steel tube for the reaction vessel was used (Figure 17). This tube was packed with the material to be charred. Before each loading, the tube was scrubbed and washed out with deionized water and acetone. Air was the reaction gas and nitrogen the inert purge gas. The volatile gases coming off the material were run through a cooling bath before being vented out of the system. The air flow was one reactor volume every five minutes. The nitrogen was run at about twice this rate. The charring process took about 3-4 hours, with maximum furnace temperature reaching 500-600°C. Stepping up the furnace temperature slowly and the excess nitrogen helped keep the pyrolyzing material from getting too hot too fast.

Due to the volume of material which had to be charred and ashed to have enough ash to test, the reactor was emptied and the char ashed in a muffle furnace at 550-650°C. This ashing could take anywhere from 4-12 hours. The woods could be ashed at a higher temperature than 650°C, but the agricultural wastes did not always give a good fluffy, fine, powdery ash. The corn cobs ashed properly at 550°C and the remaining agriculturl wastes at 600°C. Of course, lowering the temperature lengthened the time to ash the material.



Char/Ash Furnace Apparatus

Figure 17

3.6 Ash Elemental Analysis - Major and Minor Elements

The method chosen was based on ASTM D3682-78(1983) for major and minor elements in coal and coke. This test is usually a precursor to the ash fusion test. The elements of interest are Si, Al, Fe, Ca, Mg, Na, K, Ti, Mn and P. The basic purpose is getting the elements into solution which can then be analyzed for various elements by an atomic absorption spectrophotometer or colorimetrically on a visible range spectrophotometer.

One gram of a fluxing agent, $LiBO_2$ or $Li_2B_4O_7$, is weighed into a graphite crucible. Platinum is the recommended crucible in the ASTM method, but graphite has been used in the literature with no problems (Medlin 1969, Muter 1969, Muter 1975). Graphite is also cheaper and does not require any cleaning. 0.1 gram of sample is added to the crucible and the flux and sample are mixed. This mixture is placed in a muffle furnace at $1000^{\circ}C$ for 15 minutes. A liquid bead is the result. If the mixture has not beaded up, there will be problems when trying to add it to the weak acid solution. The procedure calls for a weak acid solution of HCl. The bead is added to this and heated and mixed to get the material into solution. Then various concentrations of this parent solution are made to be run on the atomic absorption spectrophotometer for different elements. An Instrumentation Laboratories 951 double beam A.A. and a Perkin Elmer 306 double beam A.A. were used. The Perkin Elmer was used to run potassium, since the I.L. 951's photomultiplier tube range did not go high enough for the preferred wavelength for K at 789 nm. Mg and Ca are plagued by chemical interferences – aluminates, silicates, sulfates and phosphate anions. These need to be removed or a releasing agent added (Medlin 1969). A 1% concentration of lanthanum is added as the releasing agent to the samples to be analyzed for Ca and Mg. This is recommended in the ASTM procedure, by the A.A. manufacturers and in the literature (Medlin 1969, Muter 1969). Lanthanum prevents the formation of compounds of Ca and Mg in the flame (Muter 1969). Another concern is Na contamination of the solutions which can occur from contaminated water or be in glassware soaps. To minimize Na contamination, wash glassware in an acid bath instead of soap and check Na content of deionized water by atomic absorption against prepared standards.

Because Si, Al and Ti are run with a nitrous oxide flame, which is a noisier and hotter flame, colorimetric procedures (using a visible range spectrophotometer) were also tried (Shapiro 1956). The colorimetric procedure for Al and Ti gave good results, though the Al was time sensitive and needed to be read after an hour. The Si procedure was time sensitive, which indicates Si not staying in solution well (common problem with spectrophotometer analysis). The blanks and standards were difficult to keep stable, because of the higher wavelength (650 nm) at which Si was being run on the visible range spectrophotometer. The ASTM procedure called for the P to be done by a colorimetric method which worked well. Higher standards were made for the Ti, Mn and P analysis, than were called for in the ASTM method.

3.7 Ash Fusion

The ash fusion test was based on the ASTM method D-1857-68(1983). This test heats ash cones at an incremental rate in a specified atmosphere (oxidizing or reducing). Four temperatures are recorded: initial deformation temperature, softening temperature, hemispherical temperature and fluid temperature as specified in the ASTM method (see Figure 3).

The ash is mixed with saturated dextrin solution until it is a pastey consistency. This is placed into a cone mold to dry. These cones are placed on a base (while the base is wet) of alundum cement or an aluminum oxide/kaolin mixture. They are placed in a electric furnace with piping for a specified atmosphere and the temperature is raised at a constant incremental rate. There is a window to observe the cones as they go through their deformations and the temperatures are recorded. There are four temperatures recorded: inital deformation temperature, softening temperature, hemispherical temperature and fluid temperature. The initial temperature is when the point of the cone has just rounded. Shrinkage or warpage of the cone is ignored if the tip remains sharp. Softening temperature is when the cone has fused down to a spherical lump in which the height is equal to the width at the base. Hemispherical temperature is the temperature at which the cone has fused to a hemispherical lump; the height is one half the width of the base. Fluid is the temperature at which the fused mass has spread out in nearly a flat layer with a maximum height of 1/16 inch.

4. RESULTS

This chapter is divided into three sections. The first section covers the fuel analyses. Data found in the literature for these analyses are also presented. Ash analyses are presented in the second section, literature data are included. The last section covers the coal ratios and coal correlations for fusion temperatures.

4.1 Fuel Analyses

The proximate analysis data for the suite of fuels investigated are summarized in Table 10 and 11. The tables contain "as received", dry and dry-ash-free (DAF) data. From the proximate analysis, it is evident that both wood and agricultutral wastes have a high volatile content on a dry or dry-ash-free basis. Moisture content is reported on an "as received" basis. This is not necessarily the same as the harvested moisture content, as some air drying of the samples has occurred. Four of the six woods exhibited moisture contents greater than twenty percent. The agricultural wastes primarily have a moisture content at or below ten percent. The woods have a much lower ash content than the agricultural wastes. Rice straw and rice hulls, compared to coals, exhibit a high ash content, 18% and 20%,

Table 10

Proximate Analysis Summary - Part 1
"As Received" Basis

Sample	Runs	% Moist	Std Dev	% Vol	Std Dev	% Fixd C	Std Dev	% Ash	Std Dev
* Category: AG WASTES									
BARLEY STRAW	7	6.449	0.462	74.799	2.370	12.754	2.150	6.000	0.549
CORN COBS	9	20.796	7.626	66.238	6.142	11.887	2.269	1.077	0.587
COTTON GIN TRASH	7	7.490	1.153	71.571	3.217	12.381	2.542	8.554	0.515
PEANUT HULLS	3	8.085	0.109	75.227	1.329	15.366	1.163	1.326	0.199
RICE HULLS	3	7.871	0.173	59.499	0.558	12.916	0.699	19.715	1.131
RICE STRAW	6	6.260	0.215	62.242	0.510	13.515	0.619	18.042	0.753
SUGAR CANE BAGASSE	3	6.964	0.049	82.319	1.314	8.942	1.264	1.775	0.639
WALNUT SHELLS	3	10.443	0.095	67.237	1.071	20.127	0.665	2.200	0.554
WHEAT STRAW	3	6.702	0.365	76.401	0.599	11.551	0.893	5.347	0.320
* Category: WOOD									
FIR BARK	4	23.095	0.848	60.073	1.033	16.040	1.350	0.863	0.315
MIXED HARDWOOD	3	22.560	2.215	68.877	1.571	7.460	0.948	1.100	0.792
PINE WEE CHIPS	3	5.944	0.085	81.967	0.394	11.767	0.367	0.323	0.055
REDWOOD BARK	10	20.337	1.079	62.019	2.195	16.688	1.663	0.953	0.838
REDWOOD SAWDUST	5	55.136	3.464	37.062	1.620	7.632	1.970	0.170	0.058
TREE CHIPS - S. CAROLINA	3	6.549	0.173	78.013	0.366	14.588	0.034	0.850	0.190

Table 11

Proximate Analysis Summary - Part 2
Dry and Dry-Ash-Free Values

Sample	Runs	% Dry Vol	% Dry Fixd C	% Dry Ash	% Daf Vol	% Daf Fix C
* Category: AG WASTES						
BARLEY STRAW	7	79.953	13.632	6.413	85.432	14.567
CORN COBS	9	83.631	15.008	1.359	84.784	15.215
COTTON GIN TRASH	7	77.369	13.383	9.246	85.252	14.747
PEANUT HULLS	3	81.840	16.716	1.442	83.038	16.961
RICE HULLS	3	64.581	14.019	21.399	82.163	17.836
RICE STRAW	6	66.356	14.408	19.234	82.160	17.839
SUGAR CANE BAGASSE	3	88.480	9.611	1.907	90.201	9.798
WALNUT SHELLS	3	75.071	22.472	2.456	76.961	23.038
WHEAT STRAW	3	81.888	12.380	5.731	86.866	13.133
* Category: WOOD						
FIR BARK	4	78.041	20.837	1.121	78.926	21.073
MIXED HARDWOOD	3	88.945	9.633	1.420	90.227	9.772
PINE WEE CHIPS	3	87.146	12.510	0.343	87.446	12.553
REDWOOD BARK	10	77.854	20.949	1.196	78.797	21.202
REDWOOD SAWDUST	5	82.609	17.011	0.378	82.923	17.076
TREE CHIPS - S. CAROLINA	3	83.480	15.610	0.909	84.246	15.753

respectively.

Table 12 contains some proximate analyses found in the literature. The experimental values for the rice hulls and walnut shells agree well with the values found in the literature. The redwood bark and fir bark also are in good agreement with published values. The proximate analyses for barley straw, wheat straw, corn cobs and cotton gin trash obtained in this laboratory study show higher volatile content, lower fixed carbon and lower ash content than those found in the literature values.

Table 13 and Table 14 contain the ultimate analysis summary. Dry and dry-ash-free results are given. Oxygen is determined by difference assuming sulfur, nitrogen and chlorine are negligible. All samples have higher oxygen content (> 38% DAF) and lower carbon content (45-55% DAF) than coals (2-30% for oxygen and 60-98% for carbon)(Volborth 1979). The woods exhibit slightly higher carbon content and slightly lower oxygen content than the agricultural wastes.

When the experimental values for the ultimate analyses are compared with the literature values in Table 15, good agreement between the values is shown. The experimental values for sugar cane bagasse, walnut shells and fir bark fall in the middle of the value ranges in the literature. The redwood bark and corn cobs C, H, O and ash values are

Table 12

Proximate Values in Selected Literature

Sample	% Vol	% Fix C	% Ash	BTU/lb	Source
Barley Straw	64.90	24.80	10.30	7440	Jenkins 1980
Coconut Shell	78.90	20.30	0.80	8630	Cruz 1977
Coconut Wood	79.70	19.30	1.00	8182	Cruz 1977
Corn Cobs	74.20	24.20	1.50	8144	Jenkins 1980
Cotton Gin Trash	63.60	18.80	17.60	7061	Jenkins 1980
Douglas Fir Bark	72.90	25.90	1.30	9570	Johnson 1951
Redwood Bark	72.60	27.00	0.50	8350	Johnson 1951
Rice Husk	61.50	15.30	23.20	6230	Cruz 1977
Walnut Shells	79.60	19.30	1.10	9076	Jenkins 1980
Walnut Shells	81.40	18.00	0.60	8910	Alliance Research 1955
Wheat Straw	68.40	24.20	7.40	7245	Jenkins 1980
White Fir Bark	74.30	24.00	1.70	8810	Johnson 1951

Table 13

Ultimate Analysis Summary
Dry Values

Sample	Runs	% C	Std Dev	% H	Std Dev	% O	Std Dev	% Ash	Std Dev
* Category: AG WASTES									
BARLEY STRAW	7	42.324	3.983	5.818	0.327	45.158	4.298	6.698	0.458
CORN COBS	6	45.756	2.925	5.784	0.864	46.807	2.905	1.651	0.294
COTTON GIN TRASH	3	44.260	1.086	5.527	0.136	42.725	1.248	7.486	0.622
PEANUT HULLS	3	50.391	1.464	6.296	0.517	41.242	1.894	2.065	0.117
RICE HULLS	2	37.798	0.253	4.953	0.003	36.352	0.278	20.901	0.535
RICE STRAW	5	38.114	0.215	5.360	0.528	38.841	0.483	17.684	0.547
SUGAR CANE BAGASSE	5	46.608	2.616	5.788	0.447	46.176	2.810	1.426	0.521
WALNUT SHELLS	2	49.035	0.134	6.025	0.064	43.705	0.644	1.230	0.453
WHEAT STRAW	2	46.352	0.277	6.311	0.020	41.754	0.279	5.580	0.536
* Category: WOOD									
FIR BARK	5	54.834	3.607	6.593	1.466	37.699	4.987	0.872	0.190
MIXED HARDWOOD	2	48.705	0.266	6.064	0.008	44.546	0.245	0.683	0.028
PINE WEE CHIPS	3	50.617	0.601	6.262	0.063	42.702	0.666	0.417	0.027
REDWOOD BARK	5	51.777	1.946	5.455	0.292	42.148	2.026	0.618	0.733
REDWOOD SAWDUST	3	52.812	1.096	6.221	0.290	40.691	1.364	0.274	0.131
TREE CHIPS - S. CAROLINA	2	49.943	0.566	5.988	0.343	43.210	0.834	0.858	0.075

Table 14

Ultimate Analysis Summary
Dry-Ash-Free with C/H and C/O Ratios

Sample	Runs	% Daf C	% Daf H	% Daf O	C/H DAF	C/O DAF
* Category: AG WASTES						
BARLEY STRAW	7	45.363	6.235	48.400	0.606	1.249
CORN COBS	6	46.525	5.881	47.593	0.659	1.303
COTTON GIN TRASH	3	47.842	5.974	46.183	0.667	1.381
PEANUT HULLS	3	51.456	6.429	42.114	0.666	1.629
RICE HULLS	2	47.783	6.261	45.955	0.635	1.386
RICE STRAW	5	46.302	6.511	47.185	0.592	1.308
SUGAR CANE BAGASSE	5	47.283	5.872	46.845	0.671	1.346
WALNUT SHELLS	2	49.648	6.100	44.251	0.678	1.495
WHEAT STRAW	2	49.092	6.684	44.222	0.612	1.480
* Category: WOOD						
FIR BARK	5	55.317	6.651	38.031	0.693	1.939
MIXED HARDWOOD	2	49.040	6.105	44.853	0.669	1.457
PINE WEE CHIPS	3	50.829	6.288	42.881	0.673	1.580
REDWOOD BARK	5	52.100	5.489	42.410	0.790	1.637
REDWOOD SAWDUST	3	52.958	6.238	40.803	0.707	1.730
TREE CHIPS - S. CAROLINA	2	50.375	6.039	43.584	0.695	1.541

Table 15

Ultimate Analysis Values in Selected Literature

Sample	% C	% H	% O	% N	% S	% Ash	Source
Bagasse	45.00	6.00	46.00			3.00	Haslam, Russell 1926
Bagasse	45.00	6.00	46.00			3.00	Johnson 1951
Bagasse - Cuba	43.20	6.00	47.90			2.90	Cruz 1977
Bagasse - Hawaii	46.20	6.40	45.90			1.50	Cruz 1977
Bagasse - Java	46.00	6.60	45.50			1.90	Cruz 1977
Bagasse - Mexico	47.30	6.10	35.30			11.30	Cruz 1977
Bagasse - Peru	49.00	5.90	43.30			1.70	Cruz 1977
Bagasse - Porto Rico	44.20	6.30	47.70			1.80	Cruz 1977
Barley Straw	39.92	5.27	43.81	1.25		9.75	Jenkins 1980
Coconut Shell	52.80	5.90	41.30			nil	Cruz 1977
Corn Cobs	44.50	5.76	46.41	0.47	0.52	1.80	Jenkins 1980
Cotton Gin Trash	39.59	5.26	36.38	2.09		16.68	Jenkins 1980
Douglas Fir Bark	56.20	5.90	36.70				Johnson 1951
Redwood Bark	51.90	5.10	42.60				Johnson 1951
Rice Hulls	39.78	5.17	39.29	0.55	0.16	14.90	Jenkins 1980
Straws	36.00	5.00	38.00	0.50		4.75	Haslam, Russell 1926
Straws	36.00	5.00	38.00	0.50		4.75	Johnson 1951
Sugar Cane Bagasse	49.48	6.20	44.32			4.00	Lamb 1977
Walnut Shells	46.90	5.69	46.00	0.37		1.04	Jenkins 1980
Walnut Shells	51.70	6.10	41.60			0.60	Alliance Research 1955
White Fir Bark	52.20	5.80	40.30				Johnson 1951
Wood - Douglas Fir	52.30	6.30	40.50			0.80	Cruz 1977
Wood - Maple	50.60	6.00	41.70			1.60	Cruz 1977
Wood - Redwood	50.40	5.80	41.30			2.30	Cruz 1977
Wood - W. Hemlock	50.40	5.80	41.30			2.30	Cruz 1977

in quantitative agreement. Table 16 contains the C/H ratios of the ultimate analyses compared with those given in the nitrogen/sulfur analysis. The difference between the C/H ratios for the ultimate analyses and the elemental analyzer range between 0.001 to 0.052 for the agricultural wastes and between 0.033 to 0.093 for woods.

The percent nitrogen and percent sulfur for dry samples are given in Table 17. The sulfur values are all less than 0.15 percent of the total sample. The woods have lower nitrogen content than the agricultural wastes, with the highest nitrogen value for the woods at .296 percent in the South Carolina tree chips. The only agricultural waste with a nitrogen content greater than one percent is peanut hulls (1.843%). Several literature nitrogen and sulfur values are listed in Table 15. The only experimental value in close agreement with the literature value is the nitrogen content for walnut shells (0.355% vs. 0.37% respectively).

Table 18 contains the experimental values for chlorine content of the total sample. The chlorine content varies widely among the agricultural wastes, with rice straw and barley straw exhibiting the highest chlorine content (1.92% and 1.71% respectively). The woods have very low chlorine content at 0.02 percent or less.

Table 16

Comparisons for C/H Ratio between the Ultimate Analyses and the Nitrogen/Sulfur Analyses

Sample	Ult Runs	C/H Ratio Ultimate	C/H Ratio Carlo Erba
* Ag Wastes *			
BARLEY STRAW	7	0.606	
CORN COBS	6	0.659	
COTTON GIN TRASH	3	0.667	
PEANUT HULLS	3	0.666	0.624
RICE HULLS	2	0.635	0.634
RICE STRAW	5	0.592	
SUGAR CANE BAGASSE	5	0.671	0.642
WALNUT SHELLS	2	0.678	0.626
WHEAT STRAW	2	0.612	0.651
* Woods *			
FIR BARK	5	0.693	0.785
MIXED HARDWOOD	2	0.669	
PINE WEE CHIPS	3	0.673	0.624
REDWOOD BARK	5	0.790	0.823
REDWOOD SAWDUST	3	0.707	0.800
TREE CHIPS - S. CAROLINA	2	0.695	0.656

Table 17

Nitrogen and Sulfur Content in Dry Samples

Sample	% N	% S
* Category: AG WASTES		
BARLEY STRAW	0.552	0.130
CORN COBS	0.317	< 0.002
COTTON GIN TRASH	0.709	0.103
PEANUT HULLS	1.843	
RICE HULLS	< 0.002	
RICE STRAW	0.319	0.020
SUGAR CANE BAGASSE	< 0.002	
WALNUT SHELLS	0.355	
WHEAT STRAW	0.689	
* Category: WOOD		
FIR BARK	< 0.002	0.074
MIXED HARDWOOD	0.128	< 0.002
PINE WEE CHIPS	< 0.002	< 0.002
REDWOOD BARK	< 0.002	0.043
REDWOOD SAWDUST	0.190	0.042
TREE CHIPS - S. CAROLINA	0.296	

Table 18

Chlorine Content of Raw Samples

Sample	% Cl
* Category: AG WASTES	
BARLEY STRAW	1.71
CORN COBS	0.52
COTTON GIN TRASH	0.63
PEANUT HULLS	0.04
RICE HULLS	0.17
RICE STRAW	1.92
SUGAR CANE BAGASSE	0.37
WALNUT SHELLS	0.39
WHEAT STRAW	0.40
* Category: WOOD	
FIR BARK	< 0.01
MIXED HARDWOOD	< 0.01
PINE WEE CHIPS	< 0.01
REDWOOD BARK	0.02
REDWOOD SAWDUST	< 0.01
TREE CHIPS - S. CAROLINA	< 0.01

The higher heating values (HHV) of dry samples from bomb calorimetry are given in Table 19. Woods have slightly greater higher heating values than the agricultural wastes. Table 20 compares higher heating values estimated from the IGT equation using the ultimate analysis data and the bomb calorimetry data. The difference is calculated from the average IGT estimate minus the average bomb calorimeter value. There is generally good agreement between the IGT equation and the laboratory data. Eight of the differences are under 150 BTU/lbm, four are between 150 and 300 BTU/lbm and three are over 300 BTU/lbm.

The C/(O+Ash) ratio is plotted against the higher heating value in Figure 18 and Figure 19. Figure 18 contains the data from this study and Figure 19 is from Haslam and Russell (1926). As the graph shows, as carbon content increases and oxygen and ash content decreases, the higher heating value increases. Higher heating value is proportional to the carbon content and inversely proportional to oxygen and ash content. Figure 18 shows the woods to be higher grade fuels than the agricultural wastes. Figure 20 is a graph which shows that the grade of fuel increases as the oxygen content decreases. The higher grade fuels have higher heating values.

Table 19

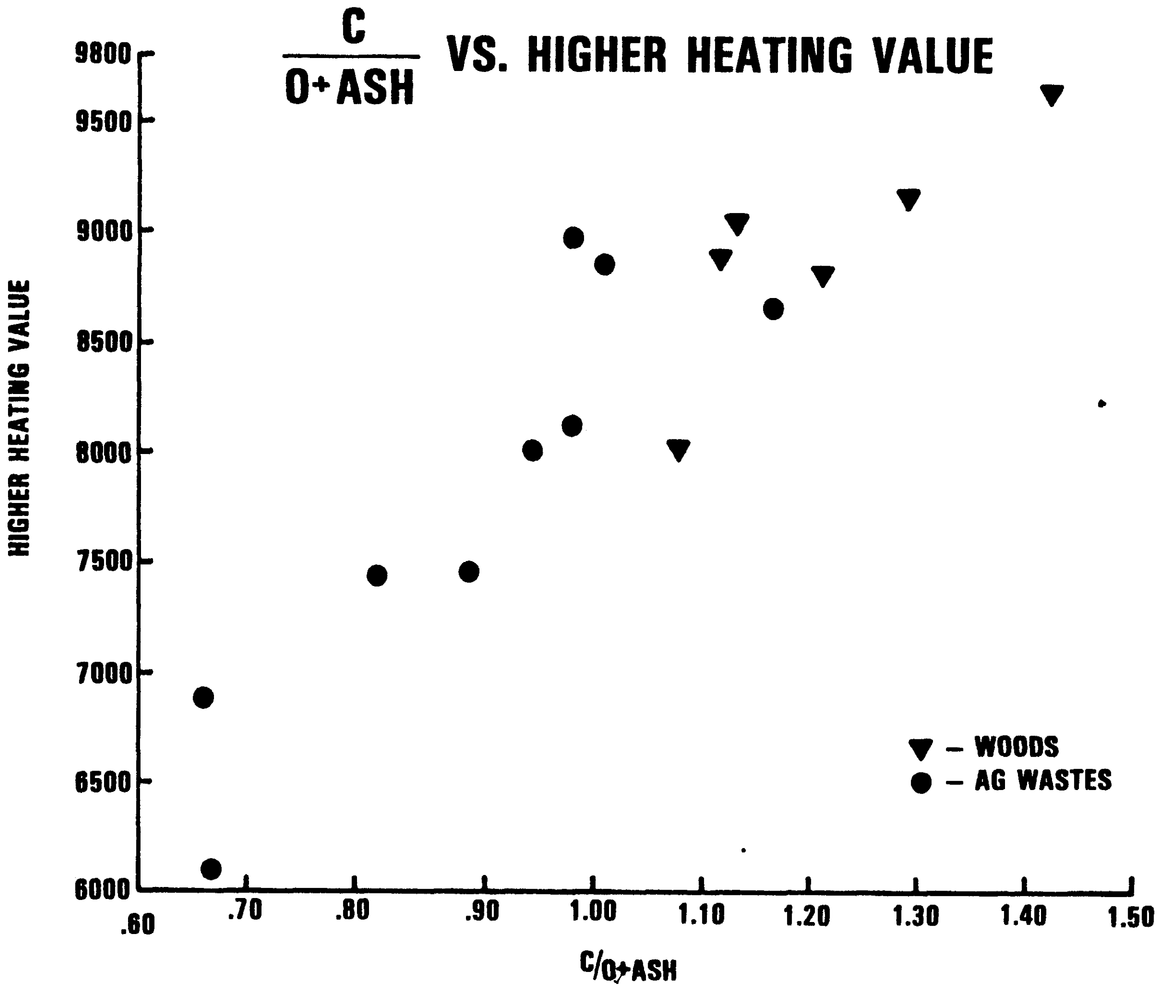
Higher Heating Value Summary

Sample	Runs	HHV cal/g	Std Dev	HHV Btu/lbm	Std Dev
* Category: AG WASTES					
BARLEY STRAW	5	4132.20	561.23	7437.60	1010.40
CORN COBS	7	4448.70	71.26	8007.40	128.15
COTTON GIN TRASH	3	4133.70	151.41	7440.60	272.55
PEANUT HULLS	2	4815.00	23.61	8667.10	42.50
RICE HULLS	3	3826.00	369.39	6886.80	664.89
RICE STRAW	7	3382.90	428.38	6089.20	771.08
SUGAR CANE BAGASSE	4	4987.50	243.36	8977.50	438.05
WALNUT SHELLS	3	4915.30	285.28	8847.60	513.51
WHEAT STRAW	2	4506.80	149.01	8112.20	268.21
* Category: WOOD					
FIR BARK	3	5359.00	151.59	9646.10	273.50
MIXED HARDWOOD	4	4455.80	134.87	8020.30	242.76
PINE WEE CHIPS	4	4937.50	289.36	8887.50	520.85
REDWOOD BARK	3	4899.50	614.27	8819.10	1105.70
REDWOOD SAWDUST	4	5098.80	720.23	9177.80	1296.40
TREE CHIPS - S. CAROLINA	3	5099.70	235.31	9164.50	402.34

Table 20

Comparing Higher Heating Values from IGT Equation and Calorimeter Data

Sample	Runs Ult	IGT cal/g	Std Dev	Runs Cal	HHV cal/g	Std Dev	Difference Ult - Cal
* Ag Wastes *							
BARLEY STRAW	7	3968.00	520.55	5	4132.20	561.23	-164.20
CORN COBS	6	4207.80	447.05	7	4448.70	71.26	-240.90
COTTON GIN TRASH	3	4100.50	162.02	3	4133.70	151.41	-33.20
PEANUT HULLS	3	4905.30	335.78	2	4815.00	23.61	90.30
RICE HULLS	2	3524.20	16.29	3	3826.00	369.39	-301.80
RICE STRAW	5	3421.00	296.53	7	3382.90	428.38	38.10
SUGAR CANE BAGASSE	5	4297.37	396.08	4	4987.50	243.36	-690.13
WALNUT SHELLS	2	4641.00	49.50	3	4915.30	285.28	-274.30
WHEAT STRAW	2	4553.40	10.37	2	4506.80	149.01	46.60
* Woods *							
FIR BARK	5	5466.40	851.69	3	5359.00	151.59	107.40
MIXED HARDWOOD	2	4604.50	31.12	4	4455.80	134.87	148.70
PINE WEE CHIPS	3	4876.80	83.69	4	4937.50	289.36	-60.70
REDWOOD BARK	5	4731.30	292.61	3	4899.50	614.27	-168.20
REDWOOD SAWDUST	3	5100.70	187.58	4	5098.80	720.23	1.90
TREE CHIPS - S. CAROLINA	2	4719.00	178.81	3	5099.70	235.31	-380.70



C/(O+Ash) versus Higher Heating Value

Figure 18

Figure 19

C/(O+Ash) versus Higher Heating Value
(Haslam & Russell)

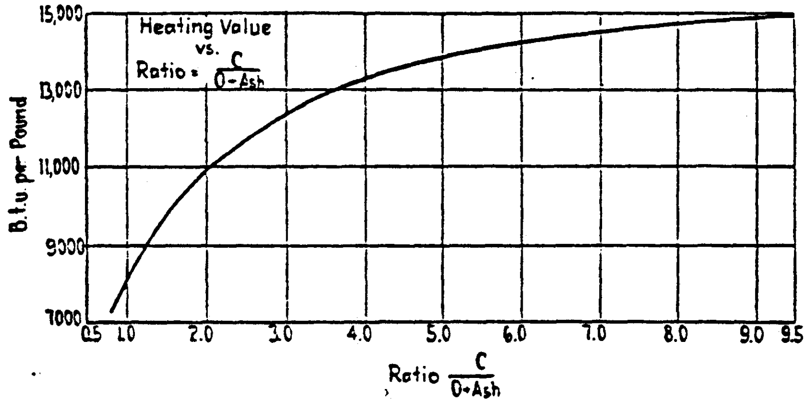
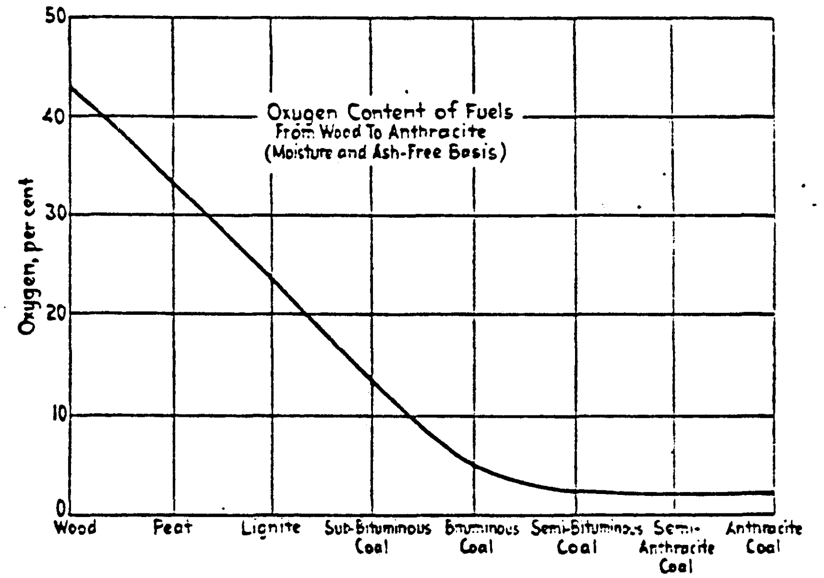


Figure 20

Oxygen Content of Fuels from Wood to Anthracite Coal



4.2 Ash Analyses

The ash elemental analysis values are given in Table 21. The woods have a higher calcium and magnesium content than agricultural wastes. Agricultural wastes contain more potassium and silica than the woods. Rice hulls and rice straw have very high silica contents (> 88%). The high silica content helps support the plant structure and prevents blast diseases (Borthakur 1980). With such high silica contents, all other elements are low. Na, K and P are the only other elements with significant amounts in rice straw and rice hulls. The straws have more silica than the other agricultural wastes. Table 22 contains the elemental values for biomass found in the literature. The literature data are scattered and not all the elements tested for in the ASTM method are found. Therefore, it is hard to assess agreement between the experimental and literature values. An example of this is rice straw. Literature values for SiO_2 are 31% and 80%, whereas the experimental value is 86.08%.

Table 23 contains the ash fusion temperatures in a reducing atmosphere. Woods have higher fusion temperatures than the agricultural wastes. The woods exhibit a tighter fusion temperature range than the agricultural wastes, in other words, the fluid temperature minus the initial

Sample	% SiO_2	% Al_2O_3	% TiO_2	% Fe_2O_3	% CaO	% MgO	% Na_2O	% K_2O	% P_2O_5	%MnO	Total
* Category: AG WASTES											
BARLEY STRAW	35.83	1.40	0.26	0.83	5.90	1.59	1.42	37.95	5.83	0.07	91.08
CORN COBS	28.24	0.46	< 0.05	0.70	< 0.30	3.58	1.25	39.16	11.87	0.05	85.66
COTTON GIN WASTE	32.06	5.42	0.38	1.86	13.91	3.65	1.96	24.08	8.61	0.07	92.00
PEANUT HULLS	12.49	2.68	0.19	1.07	5.05	3.88	2.65	35.38	13.80	0.29	77.48
RICE HULLS	96.52	0.63	< 0.05	1.04	< 0.30	0.34	0.16	3.01	0.77	0.25	103.07
RICE STRAW	86.08	< 0.40	0.10	< 0.50	< 0.30	1.73	1.58	11.71	1.74	0.69	104.83
SUGAR CANE BAGASSE	15.16	< 0.40	0.06	0.86	9.16	5.85	1.07	32.28	11.87	0.09	76.80
WALNUT SHELLS	< 4.75	< 0.40	0.06	< 0.50	22.65	2.75	9.57	15.08	4.55	0.08	60.39
WHEAT STRAW	67.88	0.58	0.06	0.96	2.14	2.53	0.56	17.52	6.76	0.06	99.05
* Category: WOOD											
FIR BARK	5.35	3.35	0.10	1.19	47.76	5.11	1.00	8.55	5.05	1.66	79.12
MIXED HARDWOOD	< 4.75	< 0.40	< 0.05	0.52	47.03	3.35	0.78	7.83	4.28	0.53	69.52
PINE WEE CHIPS	6.24	0.48	0.06	1.12	24.38	9.15	1.04	22.66	15.61	1.28	82.02
REDWOOD BARK	23.98	10.68	0.40	5.75	18.21	5.85	3.99	12.69	5.06	0.48	87.09
REDWOOD SAWDUST	33.70	6.98	0.24	7.87	26.98	6.86	2.29	5.76	6.66	0.72	98.06
TREE CHIPS - S. CAROLINA	33.61	2.85	0.19	2.20	40.84	5.87	1.03	4.98	3.42	2.15	97.14

	SiO_2 +/-	Al_2O_3 +/-	TiO_2 +/-	Fe_2O_3 +/-	CaO +/-	MgO +/-	Na_2O +/-	K_2O +/-	P_2O_5 +/-	MnO +/-
Precision	4.75	0.40	0.05	0.50	0.30	0.20	0.02	0.07	0.05	0.01

Elemental Analysis of Biomass Ash

Table 21

Table 22

Elemental Analysis of Ash in Selected Literature

Sample	% SiO2	% Al2O3	% TiO2	% Fe2O3	% CaO	% MgO
Barks	19.4 - 33.8	2.6 - 13.3	0.2	1.6 - 4.7	42.4 - 56.5	4.7 - 6.9
Cotton Gin Trash	34.00			1.0 - 2.0		
Cotton Gin Trash	5.7	0.9	0.3	3.5	39.0	1.9
Douglas Fir Bark	13.9	8.7	0.4	4.4	51.4	3.2
Redwood Bark	14.3	4.0	0.3	3.5	6.0	6.6
Rice Hulls	94.5	0.21		0.54	0.48	0.23
Rice Straw	80.00					
Rice Straw	31.0	27.0	6.0	4.0	6.0	1.0
Sugar Cane Bagasse	44.8 - 82.7	0.9 - 24.3		1.1 - 15.1	0.3 - 6.6	.04 - 4.3
Walnut Shells	8.2	2.2	0.1	5.4	50 - 80	12.0
Wheat Straw	56.8			0.5	5.8	2.0
White Fir Bark	1.7	3.2		3.2	60.8	3.0
Woods	33.8	2.6	0.2	1.6	56.5	4.7

Sample	% Na2O	% K2O	% Na2O + K2O	% P2O5	% MnO	Source
Barks	0.5 - 3.8	T - 10.4				Duzy 1965
Cotton Gin Trash						Curley 1978
Cotton Gin Trash	2.3	27.8		1.6	0.28	Jenkins 1980
Douglas Fir Bark	5.3				0.3	Johnson 1951
Redwood Bark	25.0				0.10	Johnson 1951
Rice Hulls					1.09	Borthakur 1980
Rice Straw						Horsfield 1977
Rice Straw	7.0	9.93				Jenkins 1980
Sugar Cane Bagasse			0.4 - 10.6	0.2 - 2.7		Lamb 1977
Walnut Shells	4.8				0.1	Alliance Research 1955
Wheat Straw	6.0	14.8		2.6		Jenkins 1980
White Fir Bark	10.4				3.9	Johnson 1951
Woods	0.5	0.1				Duzy 1965

Table 23

Ash Fusion Temperatures in a Reducing Atmosphere (^{o}F)

Sample	Runs	IT	ST	HT	FT	FT-IT
* Category: AG WASTES						
BARLEY STRAW	1	1590	1625	2010	2240	650
CORN COBS	2	1595	1614	1905	2000	405
COTTON GIN TRASH	1	2205	2245	2372	2445	240
PEANUT HULLS	1	2285	2330	2350	2390	105
RICE HULLS	2	> 2700				
RICE STRAW	2	> 2700				
SUGAR CANE BAGASSE	1	2175	2275	2291	2300	125
WALNUT SHELLS	1	1401	1425	1440	1630	229
WHEAT STRAW	1	1599	2345	2470	2520	921
* Category: WOOD						
FIR BARK	2	2612	2615	2626	2676	64
MIXED HARDWOOD	1	> 2700				
PINE WEE CHIPS	1	> 2700				
REDWOOD BARK	2	2233	2237	2239	2254	21
REDWOOD SAWDUST	2	2318	2363	2369	2384	66
TREE CHIPS - S. CAROLINA	1	2510	2515	2520	2525	15

IT = Initial Deformation Temperature
ST = Softening Temperature (H = W)
HT = Hemispherical Temperature (H = 1/2W)
FT = Fluid Temperature

temperature is a smaller value. Walnut shells have a very low fusion temperature. Gilbert/Commonwealth Laboratory (1981) gives the ash fusion temperatures in a reducing atmosphere for walnut shells as:

IT	ST	HT	FT	°F
1430–1450	1460–1480	1470–1490	1580–1600	GC Lab
1401	1425	1440	1630	Expt

There is less than 50 °F difference between this study and the Gilbert/Commonwealth Laboratory.

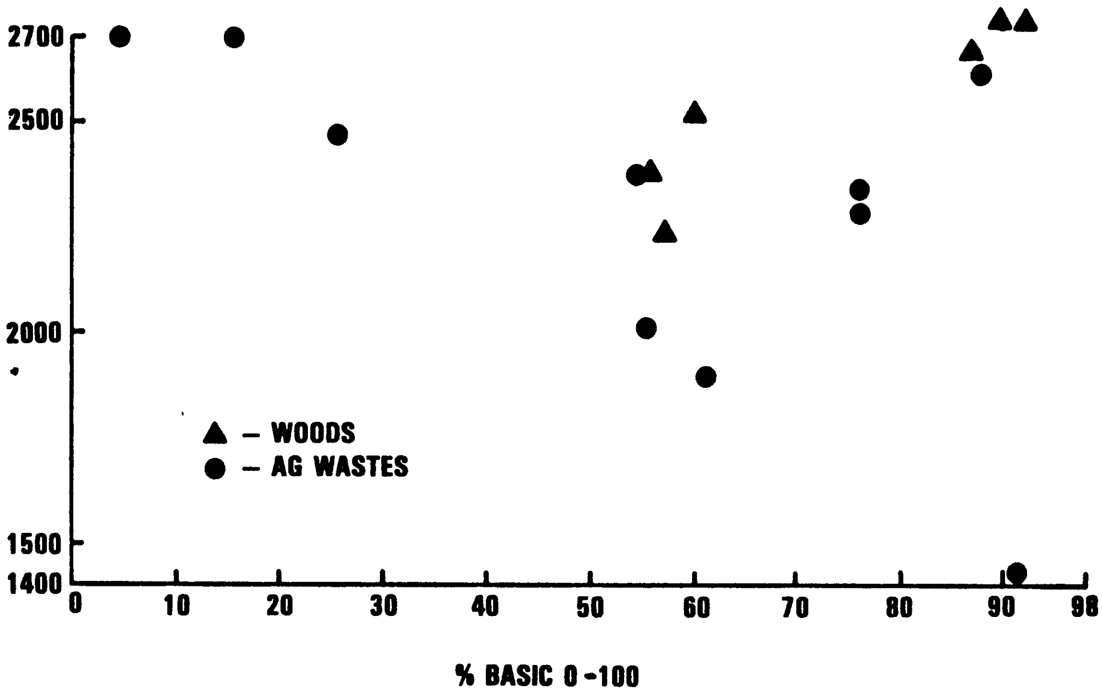
4.3 Coal Based Ratios and Correlations

Using experimental biomass elemental ash values, coal based ratios are calculated. Table 24 contains percent basic and acidic constituents, base-to-acid ratio, dolomite ratio, silica ratio, silica to alumina ratio and ash type. Woods have higher dolomite ratios and lower silica ratios than the agricultural wastes. All samples have lignite ash type ($CaO + MgO > Fe_2O_3$), except for the rice hulls. Figure 21 and Figure 22 are plots of percent basic constituents versus hemispherical fusion temperature in a reducing atmosphere. Figure 22 includes the dolomite ratio. Figure 21 shows a lowering of the hemispherical fusion temperatures between 50 and 60 percent basic

Table 24

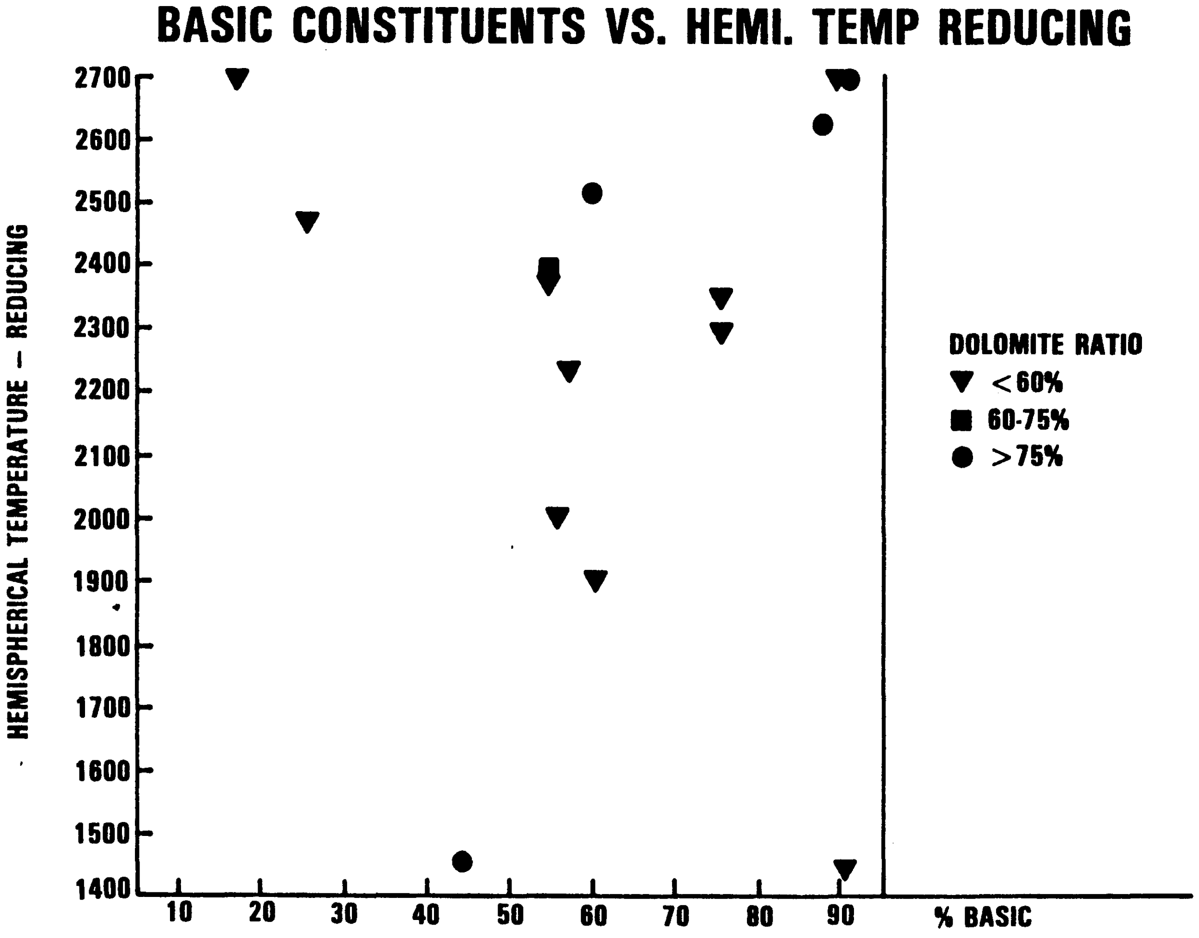
Coal Correlations and Ratios

Sample	% Base	% Acid	Base/Acid Ratio	Dolomite Ratio	Silica Ratio	Si/Al Ratio	IT	ST	HT	FT	Ash Type
* Category: AG WASTES											
BARLEY STRAW	55.99	44.01	1.27	15.71	81.16	25.59	1590	1625	2010	2240	LIGNITE
CORN COBS	61.01	38.99	1.56	8.62	86.05	61.39	1595	1614	1905	2000	LIGNITE
COTTON GIN TRASH	54.56	45.44	1.20	38.63	62.28	5.92	2205	2245	2372	2445	LIGNITE
PEANUT HULLS	75.77	24.23	3.13	18.59	55.54	4.66	2285	2330	2350	2390	LIGNITE
RICE HULLS	4.75	95.25	0.05	13.20	98.29	98.29	> 2700				HIGH RANK
RICE STRAW	15.45	84.55	0.18	12.83	97.14	215.20	> 2700				LIGNITE
SUGAR CANE BAGASSE	75.91	24.09	3.15	30.50	48.86	37.90	2175	2275	2291	2300	LIGNITE
WALNUT SHELLS	90.66	9.34	9.70	50.25	15.50	11.88	1401	1425	1440	1630	LIGNITE
WHEAT STRAW	25.71	74.29	0.35	19.70	92.34	117.03	1599	2345	2470	2520	LIGNITE
* Category: WOOD											
FIR BARK	87.85	12.15	7.23	83.12	9.01	1.60	2612	2615	2626	2676	LIGNITE
MIXED HARDWOOD	91.96	8.04	11.44	84.66	8.54	11.87	> 2700				LIGNITE
PINE WEE CHIPS	89.59	10.41	8.61	57.46	15.26	13.00	> 2700				LIGNITE
REDWOOD BARK	57.01	42.99	1.33	51.75	44.58	2.25	2233	2237	2239	2254	LIGNITE
REDWOOD SAWDUST	54.87	45.13	1.22	68.01	44.69	4.83	2318	2363	2369	2384	LIGNITE
TREE CHIPS - S. CAROLINA	59.98	40.02	1.50	85.05	40.73	11.79	2510	2515	2520	2525	LIGNITE



Percent Basic Constituents versus Hemispherical Fusion Temperatures in a Reducing Atmosphere (°F)

Figure 21

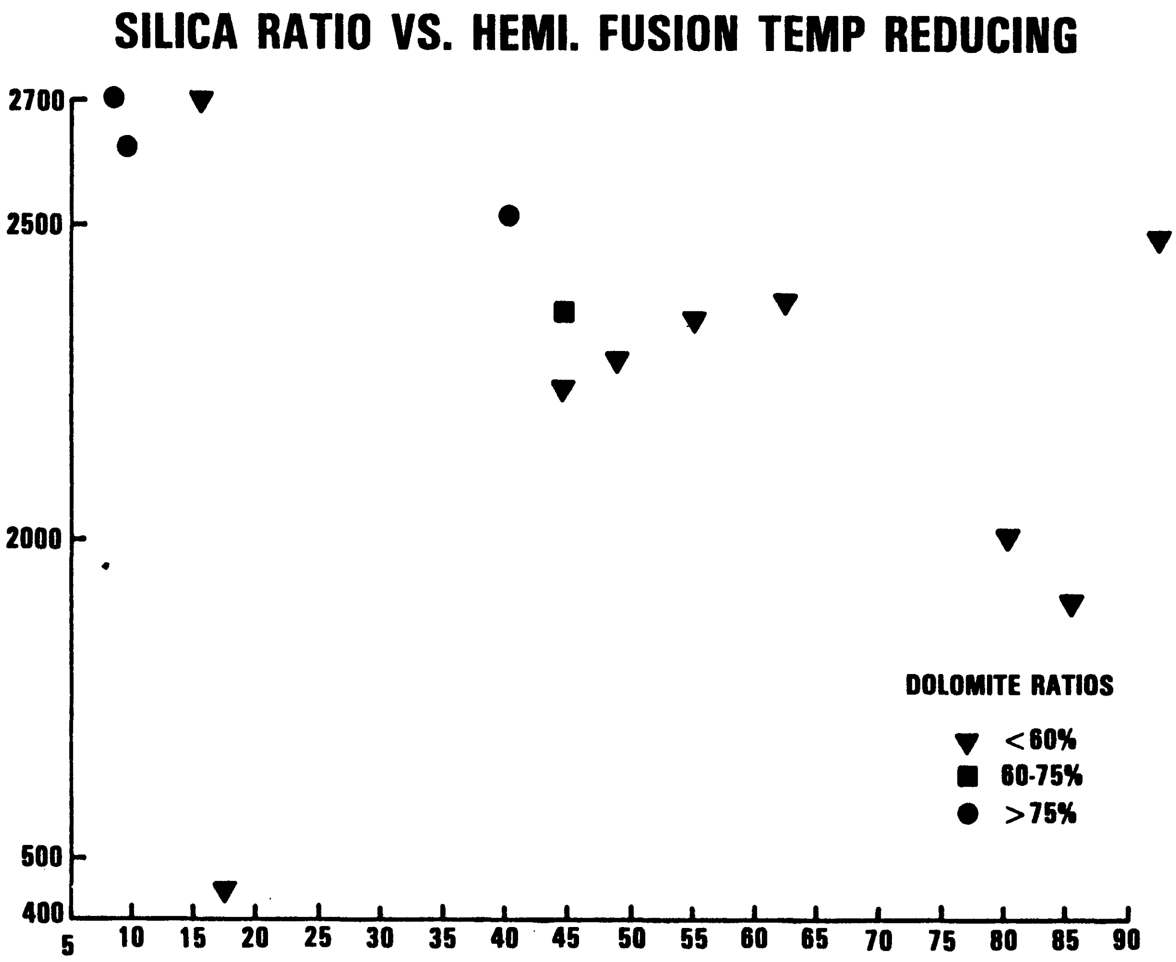


Percent Basic Constituents and Percent Dolomite Ratio versus Hemispherical Fusion Temperatures in a Reducing Atmosphere (^{o}F)

Figure 22

constituents. Coals exhibit a lowering of the hemispherical fusion temperature when the basic constituents are between approximately 30 - 55 percent (see Figure 7). For coals, Duzy (1965) shows in Figure 6, that high basic content with high dolomite ratios indicates high hemispherical fusion temperatures. The woods have higher dolomite ratios, basic content and hemispherical fusion temperatures than the agricultural wastes. Silica and dolomite ratios are plotted against the hemispherical fusion temperatures (reducing atmosphere) in Figure 23. In Figure 5, Duzy (1965) shows that coals with high dolomite ratios and low silica ratios have higher ash hemispherical fusion temperatures. The woods exhibit this behavior.

Based upon the above analyses and ratios, coal correlations are developed for biomass. The calculated softening temperatures using equations proposed by Sondreal and Ellman (1975) are given in Table 25. The experimental fusion temperature is given first, with three values calculated from the three different equations proposed. The difference between experimental and calculated temperatures are given. The equations for bituminous and lignite coals predicts the fusion temperature within 500 ^{o}F, except for walnut shells. Table 26 contains the calculated hemispherical fusion temperatures using Bryers and Taylor's equations (1976). The experimental



Silica Ratio and Dolomite Ratio versus Hemispherical Fusion Temperatures in a Reducing Atmosphere (^{o}F)

Figure 23

Table 25

Sondreal & Ellman: Equations for Predicting Ash Softening Temperatures for Western Lignites (Reducing Atmosphere °F)

Sample	Soft Temp	Calc ST Nat Lig	ST - Calc	Calc ST Lig w/ Add	ST - Calc	Calc ST Bit + Lig	St - Calc	Ash Type
* Category: AG WASTES								
BARLEY STRAW	1625	1417.70	207.30	1477.48	147.52	2075.47	-450.47	LIGNITE
CORN COBS	1614	981.00	633.00	1377.72	236.28	2100.12	-486.12	LIGNITE
COTTON GIN TRASH	2245	2026.33	218.67	1756.14	488.86	2062.88	182.12	LIGNITE
PEANUT HULLS	2330	1452.85	877.15	1672.43	657.57	2187.70	142.30	LIGNITE
RICE HULLS	> 2700	777.51	1922.49	753.23	1946.77	2906.38	-206.38	HIGH RANK
RICE STRAW	> 2700	760.65	1939.35	845.11	1854.89	2608.16	91.84	LIGNITE
SUGAR CANE BAGASSE	2275	1740.66	534.34	1839.97	435.03	2215.51	59.49	LIGNITE
WALNUT SHELLS	1425	2605.48	-1180.48	2287.51	-862.51	2638.04	-1213.04	LIGNITE
WHEAT STRAW	2345	1001.33	1343.67	1069.10	1275.90	2332.30	12.70	LIGNITE
* Category: WOOD								
FIR BARK	2615	3212.98	-597.98	2560.01	54.99	2984.34	-369.34	LIGNITE
MIXED HARDWOOD	> 2700	3370.82	-670.82	2583.72	116.28	3135.73	-435.73	LIGNITE
PINE WEE CHIPS	> 2700	2709.63	-9.63	2358.10	341.90	2685.34	14.66	LIGNITE
REDWOOD BARK	2237	2295.65	-58.65	2006.29	230.71	2116.02	120.98	LIGNITE
REDWOOD SAWDUST	2363	2493.26	-130.26	2066.33	296.67	2204.60	158.40	LIGNITE
TREE CHIPS - S. CAROLINA	2515	2820.68	-305.68	2283.60	231.40	2425.02	89.98	LIGNITE

Soft Temp – Softening temperature experimental

Calc ST – Calculated softening temperature

St – Calc – Experimental Soft Temp minus Calc ST

Table 26

Bryers & Taylor: Equations for Predicting Ash Hemispherical Temperatures (Reducing Atmosphere °F)

Sample	Hemi Temp	Calc HT Lig + Wym Si/Al > 1.	HT - Calc	Calc HT Wyoming Si/Al > 1.	HT - Calc	Calc HT Wyoming Si/Al ~ 1.	HT - Calc	Si/Al
* Category: AG WASTES								
BARLEY STRAW	2010	2842.74	-832.74	2794.90	-784.90	2977.17	-967.17	25.59
CORN COBS	1905	2840.55	-935.55	2792.83	-887.83	2975.56	-1070.56	61.39
COTTON GIN TRASH	2372	2843.11	-471.11	2795.24	-423.24	2977.44	-605.44	5.91
PEANUT HULLS	2350	2835.46	-485.46	2788.03	-438.03	2971.82	-621.82	4.66
RICE HULLS	> 2700	2861.51	-161.51	2812.60	-112.60	2990.91	-290.91	153.20
RICE STRAW	> 2700	2857.44	-157.44	2808.76	-108.76	2987.94	-287.94	215.20
SUGAR CANE BAGASSE	2291	2835.46	-544.46	2788.03	-497.03	2971.82	-680.82	37.90
WALNUT SHELLS	1440	2830.02	-1390.02	2782.90	-1342.90	2967.82	-1527.82	11.87
WHEAT STRAW	2470	2853.75	-383.75	2805.28	-335.28	2985.24	-515.24	117.03
* Category: WOOD								
FIR BARK	2626	2831.10	-205.10	2783.92	-157.92	2968.62	-342.62	1.59
MIXED HARDWOOD	> 2700	2829.66	-129.66	2782.56	-82.56	2967.56	-267.56	11.87
PINE WEE CHIPS	> 2700	2830.38	-130.38	2783.24	-83.24	2968.09	-268.09	13.00
REDWOOD BARK	2239	2842.01	-603.01	2794.21	-555.21	2976.64	-737.64	2.24
REDWOOD SAWDUST	2369	2843.11	-474.11	2795.24	-426.24	2977.44	-608.44	4.82
TREE CHIPS - S. CAROLINA	2520	2841.28	-321.28	2793.52	-273.52	2976.10	-456.10	11.79

hemispherical temperature is given first, and the three calculated values with their difference from experimental values are given. The equations consistently overpredict the fusion temperature. Tables 27, 28 and 29 contain the calculated results using Winegartner and Rhodes's fusion prediction equations based on Eastern and Western coals. The experimental fusion temperatures are given first in the table and the calculated values last. These correlations do a poor job of predicting the biomass fusion temperatures.

In Table 27, the initial deformation temperatures and the hemispherical temperatures have some very large ash fusion predictions (> than 10^5). One of the factors for these temperature predictions involves an exponential based on the base-to-acid ratio ($\exp(10^{-1}((\text{Base/Acid})-1)^2)$ (see Appendix 3). The low value for the base-to-acid ratio is 0.05 and the high value for this ratio is 11.44 (see Table 24). For the initial deformation temperature, this exponential factor is multiplied by -4560. The exponential is multiplied by 1813.42 for the hemispherical temperature prediction. That means for the initial deformation temperature, that exponential factor can vary from -4990.6 to -24688616.2. This same factor is in the Western coals prediction equations (Table 29).

Sample		IT	ST	HT	FT	Calc Initial Temp	Calc Soft T	Calc Hemi Temp	Calc Fluid T
* Category: AG WASTES									
BARLEY STRAW		1590	1625	2010	2240	16865.67	1780.959	574.47	2736.305
CORN COBS		1590	1614	1905	2000	75979.50	1170.481	579.94	2118.923
COTTON GIN WASTE		2205	2245	2372	2445	8789.80	2367.951	665.08	3192.436
PEANUT HULLS		2285	2330	2350	2390	2148.37	429.138	1662.23	1369.107
RICE HULLS	>	2700	2700	2700	2700	425468.61	2790.432	3376.51	2732.707
RICE STRAW	>	2700	2700	2700	2700	849477.36	2439.268	2723.09	2484.312
SUGAR CANE BAGASSE		2175	2275	2291	2300	29155.81	844.184	1561.35	1689.348
WALNUT SHELLS		1401	1425	1440	1630	-1327286892000.00	9996.560	527835236700.00	8367.435
WHEAT STRAW		1599	2345	2470	2520	256827.83	2218.144	1992.38	2472.724
* Category: WOOD									
FIR BARK		2612	2615	2626	2676	-9190103971.00	5897.092	3654731099.00	6113.735
MIXED HARDWOOD	>	2700	2700	2700	2700	0.00	7387.235	10113660950000000.00	6443.474
PINE WEE CHIPS	>	2700	2700	2700	2700	-2286645380.00	2480.533	909362438.70	2612.488
REDWOOD BARK		2233	2237	2239	2254	8591.44	3109.996	1271.31	3737.960
REDWOOD SAWDUST		2318	2363	2369	2384	13813.57	4093.167	905.79	4824.359
TREE CHIPS - S. CAROLINA		2510	2515	2520	2525	24428.70	5444.830	-438.96	7149.193

Winegartner & Rhodes Fusion Equations
using Eastern & Western Coals

Table 27

Table 28

Winegartner & Rhodes: Fusion Equations using Eastern Coals

Sample		IT	ST	HT	FT	Calc Initial Temp	Calc Soft T	Calc Hemi T	Calc Fluid T
* Category: AG WASTES									
BARLEY STRAW		1590	1625	2010	2240	9232.669	4343.666	4078.404	-8185.753
CORN COBS		1590	1614	1905	2000	48194.511	1884.940	4022.371	-8363.902
COTTON GIN WASTE		2205	2245	2372	2445	2095.702	5806.873	4274.520	-7690.784
PEANUT HULLS		2285	2330	2350	2390	1154.459	-2601.393	4054.390	-8345.616
RICE HULLS	>	2700	2700	2700	2700	302144.931	2858.245	4094.414	-8283.069
RICE STRAW	>	2700	2700	2700	2700	585709.530	2991.931	4054.390	-8263.175
SUGAR CANE BAGASSE		2175	2275	2291	2300	18282.118	-781.314	4010.364	-8205.154
WALNUT SHELLS		1401	1425	1440	1630	-22458.633	12891.174	4006.362	-10595.297
WHEAT STRAW		1599	2345	2470	2520	177749.042	3245.855	4062.395	-8288.309
* Category: WOOD									
FIR BARK		2612	2615	2626	2676	-30751.977	21776.444	4030.376	-4036.815
MIXED HARDWOOD	>	2700	2700	2700	2700	-64992.498	37888.456	4006.362	-4321.333
PINE WEE CHIPS	>	2700	2700	2700	2700	-25766.282	9438.800	4006.362	-7285.045
REDWOOD BARK		2233	2237	2239	2254	2434.039	6997.195	4406.598	-7665.230
REDWOOD SAWDUST		2318	2363	2369	2384	2659.594	11537.791	4370.577	-6788.658
TREE CHIPS - S. CAROLINA		2510	2515	2520	2525	7539.909	21064.394	4250.506	-14279.323

Table 29

Winegartner & Rhodes: Fusion Equations using Western Coals

Sample		IT	ST	Calc Initial Temp	Calc Soft T
* Category: AG WASTES					
BARLEY STRAW		1590	1625	4324.73	-78333346.66
CORN COBS		1590	1614	4436.73	-84382719.60
COTTON GIN WASTE		2205	2245	5838.09	-45188439.60
PEANUT HULLS		2285	2330	2376.52	-32643373.90
RICE HULLS	>	2700	2700	2444.13	-120527875.50
RICE STRAW	>	2700	2700	2498.99	-115636467.40
SUGAR CANE BAGASSE		2175	2275	3263.18	-24286513.19
WALNUT SHELLS		1401	1425	-729946667600.00	1100856888000.00
WHEAT STRAW		1599	2345	3529.65	-103921034.60
* Category: WOOD					
FIR BARK		2612	2615	-5054137716.00	7621553742.00
MIXED HARDWOOD	>	2700	2700	0.00	21093169780000000.00
PINE WEE CHIPS	>	2700	2700	-1257553802.00	1894463878.00
REDWOOD BARK		2233	2237	5678.26	-24300637.33
REDWOOD SAWDUST		2318	2363	8298.59	-24302831.22
TREE CHIPS - S. CAROLINA		2510	2515	14085.52	-32654205.50

Sample		HT	FT	Calc Hemi T	Calc Fluid T
* Category: AG WASTES					
BARLEY STRAW		2010	2240	428.97	439.46
CORN COBS		1905	2000	296.51	453.81
COTTON GIN WASTE		2372	2445	597.74	564.34
PEANUT HULLS		2350	2390	1689.35	1964.79
RICE HULLS	>	2700	2700	-442.81	83.32
RICE STRAW	>	2700	2700	-448.71	53.49
SUGAR CANE BAGASSE		2291	2300	1783.91	1917.96
WALNUT SHELLS		1440	1630	598356082700.00	673921206600.00
WHEAT STRAW		2470	2520	-272.89	125.87
* Category: WOOD					
FIR BARK		2626	2676	4143019158.00	4666232232.00
MIXED HARDWOOD	>	2700	2700	11464885580000000.00	12912761700000000.00
PINE WEE CHIPS	>	2700	2700	1030858843.00	1161043744.00
REDWOOD BARK		2239	2254	998.34	1024.24
REDWOOD SAWDUST		2369	2384	1281.93	1222.10
TREE CHIPS - S. CAROLINA		2520	2525	2289.01	1708.88

5. DISCUSSIONS and CONCLUSIONS

Fifteen biomass samples are analyzed for proximate, ultimate and elemental composition, ash fusion temperatures are determined and literature correlations are employed to relate sample analyses to fusion temperatures. Generally, resultant higher heating values were predictable with the IGT equation. The ash characteristics varied over a wide range for the biomass samples. The ash fusion temperatures for woods are as expected from ash analyses. Ash fusion prediction equations did a poor job of estimating the fusion temperatures of biomass when compared with experimental ash fusion data. The small data base used is this study makes it difficult to determine the usefulness of the coal correlations.

The fuel analyses show biomass can be a suitable fuel source. Biomass feedstocks as supplementary fuels can help cut costs, reduce diposal problems and utilize low grade fuel sources. When using biomass feedstocks as the primary fuel source, a few things should be noted. The best biomass fuel source would have a low ash content, low moisture content, high carbon content and ash that would not fuse at lower furnace temperatures (< 2100 ^{o}F). Particulates are the major air pollution concern. This study shows wood ash should not be troublesome, since the ash content is less than 2.0 %. The woods display slightly higher carbon content and ash fusion temperatures than the agricultural wastes. The moisture content should be a consideration, since the woods in this study exhibit high moisture (up to 55 %). Since the agricultural wastes display a wide variety of fusion temperatures, total ash content and elemental content, these fuels should be chosen with care.

5.1 Fuel Analyses

The three main components of biomass are lignin, cellulose and hemicellulose (Lally 1983). The molar ash-free C/H ratios of cellulose and lignin are 0.6 and 1.0, respectively. Their C/O ratios are 1.2 and 3.8 (Hubis 1983). The ultimate data has C/H ratios ranging from 0.606 to 0.790, falling between lignin and cellulose values (Table 14). The C/H ratios collected by the elemental analyzer range from 0.624 to 0.823 (Table 16). The C/O ratios of the experimental data ranged from 1.25 to 1.94, with an average of 1.50. This agrees with the biomass data Hubis collected; the C/H average was 0.68 and the C/O average was 1.46.

The IGT equation predicts higher heating values and is based on an unspecified coal data base. According to Graboski and Bain (1979), the IGT equation gives an average error of +/- 150 BTU/lbm for char and fresh biomass. Eight of the fifteen samples in this study have a difference of less than 150 BTU/lbm between experimental data and the IGT prediction (Table 20). The high standard deviation for the bomb calorimetry data is due to the difficulty in combusting non-compacted material. The high standard deviation for the IGT equation is due to the high standard deviation in the ultimate analysis. Barley straw and fir bark have the highest standard deviation for predicted values from the IGT equation. Refering to Table 13, both samples have the highest standard deviation for carbon, hydrogen and oxygen. In the ultimate analysis, sampling problems, as discussed in the experimental procedures, and experimental error are the likely reasons for high standard deviation.

The total of the elements in the ash, based on atomic absorption and visible spectrophotometry, varies from 60.39% to 104.83%. It should be noted that the cumulative precision of the elemental analysis test (given in Table 21) is +/- 6.35%. The ten elements shown in Table 21, are the major elements tested for in coals. Based on this study, these same ten elements are not consistently the primary constituents. Volatility of Na, K or P salts or other compounds not tested for are a reason for ash totals less than 100%.

5.2 Ash Analyses

The ash fusion data in this study indicates that high silica content or high calcium and/or magnesium content translates into high ash fusion temperatures. For coals, increases in silica, calcium or magnesium drive the fusion temperature higher (Sondreal 1975). Rice hulls and rice straw exhibited high fusion temperatures and very high SiO_2 fcontent, with K_2O being a minor contributor. This is inconsistent with the literature which suggests that these ashes exhibit rather low temperatures. Figure 24 is a phase diagram of the SiO_2 - K_2O system. This phase diagram indicates that with a silica content of 80 % or greater, between 800 to 900 °C (1472 - 1652 °F) a sticky liquid mass should be observed. The ash is becoming liquid with silica crystalline formations. Pure K_2O decomposes at 350 °C. In the present experiments, the possibility exists that the potassium - silica mixture fused together in a cone shape with minimal deformation due to the high silicon crystalline formations in the liquid mass.

The woods have higher ash fusion temperatures than the agricultural wastes. They also have more CaO and MgO than the agricultural wastes, indicating that CaO and MgO do contribute to increases in ash fusion temperatures. Figure 25 is a phase diagram of CaO and MgO. This diagram shows

Figure 24

K_2O – SiO_2 Phase Diagram (°C)
(Levin 1974)

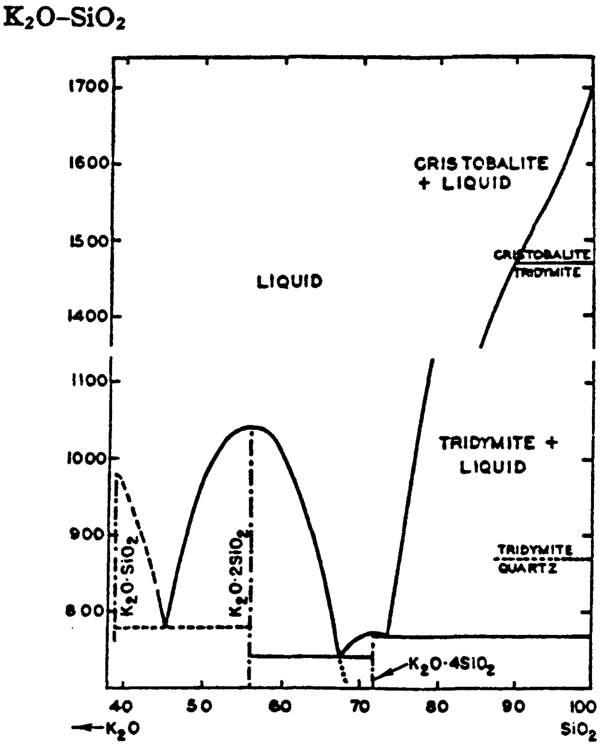
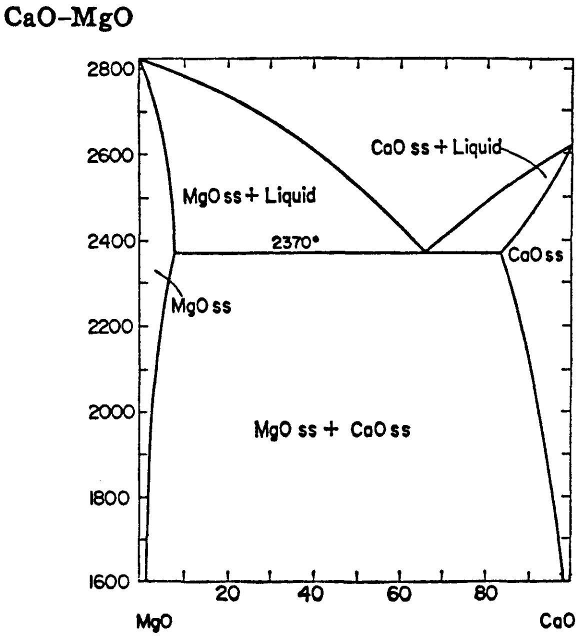


Figure 25

CaO – MgO Phase Diagram (^{o}C)
(Levin 1974)



various combinations of CaO and MgO stay solid till 2370°C.

Jenkins (1980) states that pelleted rice hulls slag severely (Table 8). This behavior is not indicated by the ash fusion temperatures on rice hulls in this study. Rice hulls are the only fuel which exhibited slagging in the bomb calorimeter, though ashing the material was no problem. High Na and K content lowers ash fusion temperature and may cause slagging (Sondreal & Ellman 1975). Ashing allows elements, such as Na and K to volatilize. Jenkins data for cotton gin waste, in Table 9, shows that the elements found in the ash are not the same percentages as the elements found in the slag. Many factors affect the ash at the grate in the firebox. Settling out of the heavier components can alter the combination of elements in the ash.

Based upon elemental analyses, there is no clear explanation for the lower ash fusion temperatures exhibited by corn cobs and walnut shells. The walnut shells have forty percent of the total ash unaccounted for in this data. Alliance Research (1955) elemental analysis for walnut shells, has CaO (50 to 80%) and MgO (12%) as the major constituents in the ash (Table 22). This study has CaO (22.65%), K_2O(15.08%), Na_2O (9.57%), P_2O_5 (4.55%) and MgO (2.75%) as the major components in walnut shells (Table 21). To achieve good quality ash without aggregate material, for corn cobs, the ashing temperature was lowered. Corn cobs and walnut shells do not have elemental compositions which would indicate low ash fusion temperatures.

Chlorine content is calculated on total sample using neutron activation analysis. This procedure eliminates losses from volatilization during ashing. Na and K content are based on a different analytical technique than Cl content. The sample has to be ashed to determine Na and K content. The melting point of pure sodium is 97.81°C and the melting point of sodium chloride is 801°C. The melting point of pure potassium is 63.65°C, while potassium chloride is 770°C (CRC 1981).

5.3 Coal Correlations

All of the samples in this study except the rice hulls, have lignite type ash. The magnitude in analytical imprecision is sufficient to change rice hulls from high rank ash type to lignite ash type. In Figures 21, 22 and 23, basic constituents, silica ratios and dolomite ratios versus hemispherical fusion temperatures are inconclusive when compared to similiar relations found in Duzy's graphs (Figures 5–7).

Sondreal/Ellman's bituminous and lignite coal equation gives fusion temperature results within 500 °F to experimental data, except for walnut shells (Table 25). None of these correlations give good results when compared with experimental values. Of the three correlations, Sondreal/Ellman use a data base with Western lignite coal ash. This database is the most similar in ash type to biomass ash. Bryers/Taylor equations place an emphasis on silica/alumina ratio and basic constituents. The samples tested range from 1.6 to 215.2 for the silica/alumina ratio and 4.75 to 92.0% for the basic constituents. Their equations are second order polynomial regressions on a small database (< 50 samples), with little elemental variation. The equations consistently overpredict the values for hemispherical fusion temperatures (Table 25).

Winegartner/Rhodes ash fusion equations fit poorly to the experimental temperatures (Table 27-29). The data base used to formulate the equations employed 1212 samples of homogeneous coal type. There are fifty-one possible correlation factors in their equation. The regression program evaluates factors for mathematical significance within the data base. This program must be reset when new coals are studied, since empirically derived correlation factors change. Therefore, these equations can not be expected to give values similar to the experimental biomass temperatures.

6. RECOMMENDATIONS FOR FUTURE WORK

Low temperature ashing procedures should be explored. This method is preferrable for analyzing for volatile elements. Any analytical procedure which utilizes a whole sample is another way to analyze the suspected volatile elements, since sample preparation and ashing could volatilize these elements. Neutron activation analysis is able to ultilize the whole sample without extensive sample preparation. It also be used to scan for elements. This would be advantageous with the agricultural wastes. Crops are grown with various soil and fertilizer conditions, different water sources and during different growing seasons. These all have an affect on mineral availability and uptake into the plant matrix. Slags could be analyzed for element content using nuetron activation analysis.

X-ray fluorescence (XRF) is another analytical tool which is able to scan for elements contained in the samples. The sample must be ground to -200 mesh and pelletized. This is to provide a uniform surface for x-ray bombardment and the sample is usually under vacumn. This works better with biomass ash than ground total sample. The higher moisture contents in biomass make grinding to -200 mesh difficult. Also, ashing concentrates the inorganic matter. The precision of the XRF for quantitative measurements is not as high as the atomic absorption spectrophotometer. Therefore, scan the ash for elements using the XRF and calculate the quantity of the suspected element using the atomic absorption spectrophotometer.

Statistical correlations could be developed by expanding the elemental ash analyses and ash fusion temperatures database for biomass fuels. Actual laboratory tests with biomass as the fuel feedstock would be very useful. Most analytical procedures cannot imitate the true conditions that the fuels are subjected to. Using biomass as a supplementary fuel in these laboratory set-ups would provide information on ash blending.

REFERENCES CITED

Alliance Research Center, 1955. " Analysis of Walnut Shells." courtesy of Garbeff,T., Sun-Diamond Co, California

Borthakur, P.C., Saikia, P.C., Dutta, S.N. 1980. "Physico Chemical Charateristics of Silica from Paddy Husk, its Reactivity and Probable Field of Application." Indian Ceramics, vol. 23, no. 2, May 1980. pp 25-29

Brudenell, W. N., Holland, R. J. 1981. "Sunflower Seed Hulls as Supplementary Fuel to Coal-Fired Power Plants." American Society of Mechanical Engineers, Publ. #81-JPGG-Fu-10

Bryers, R.W., Taylor, T.E. 1976. "An Examination of the Relationship Between Ash Chemistry and Ash Fusion Temperature in Various Coal Size and Gravity Fractions Using Polynomial Regression Analysis." Journal of Engineering for Power, vol. 98, 1976. pp 528-539

Corey, R.C. 1962. "Measurement and Significance of the Flow Properties of Coal-Ash Slag." United States Bureau of Mines Bulletin #618

Cruz, I.E. 1976. "Producer Gas from Agricultural Wastes - Its Production and Utilization in a Converted Oil-Fired Boiler." Resource Recovery and Conservation, vol. 2, 1976/1977. pp 241-256

Curley, R.G., Miller, G.E., Knutson, J.D. Brooks, C.R. Struckmeyer, T., Goss, J.R., Thompson, J.F. 1978. "Screening Cotton Gin Trash to Remove Soil Materials." Agricultural Engineering Dept., University of California, Davis, Calif.

Duzy, A.F. 1965. "Fusibility-Viscosity of Lignite-Type Ash." American Society of Mechanical Engineers Publ. # 65-WA/FU-7

Fryer, J.F. 1974. "Proximate Analysis." Symposium on Coal Evaluation. Oct 31 - Nov 1, 1974, Calgary, ALberta. pp 18-20

Garbeff, T.J. 1981. "Biomass Burning - Diamond Walnut Becomes Energy Self-Sufficient Food Processing." June 1981. pp 136-138

Gilbert/Commonwealth Laboratory Services, 1981. "Analysis of Walnut Shells (Ash Fusion - Reducing Atmosphere)." Gilbert Associates, Inc., P.O. Box 1498, Reading, Pa. 19603

Graboski, M.S., Bain, R. 1979. "Properties of Biomass Relevant to Gasification." Chap 3 in A Survey of Biomass Gasification, vol. 2, Priciples of Gasification. Solar Energy Research Institute Technical Report 33-239, July 1979. pp 21-65

Haggin, J., Krieger, J.H. 1983. "Biomass Becoming More Important in U.S. Energy Mix." Chemical & Engineering News, March 14, 1983. pp 28-30

Haslam, R.T., Russell, R.P. 1926. Fuels and Their Combustion. 1st Ed. Mcgraw-Hill

Hayes, J.C. 1973. "Measurement of the Thermal Output of Agricultural Residues." Agricultural Engineering Dept., Clemson University, Clemson, South Carolina

Herman, D.R. 1981. "The Rate of Pyrolysis of Densified Pine." M. Sc. Thesis, Colorado School of Mines, Golden, Colorado

Horsfield, B.C., Jenkins, B.M., Becker, C. 1977. "Agricultural Residues as an Alternative Source of Energy for the Pacific Gas and Electric Co." Dept. of Agricultural Engineering Research report, University of California, Davis, California. July 1977.

Horsfield, B., Williams, R.O. 1978. "Energy for Agriculture and the Gasification of Crop Residues." Energy Source, vol. 3, no. 3/4, 1978. pp 277-291

Jenkins, B.M. 1980. "Downdraft Gasification Characteristics of Major California Residue-Derived Fuels." Ph.D. Dissertation, University of California, Davis, California

Lally, K.J. 1983. "The Design, Fabrication and Operation of a High Pressure, High Temperature Thermobalance for Wood Gasification Studies." M. Sc. Thesis, Colorado School of Mines, Golden, Colorado

Lamb, B.W., Bilger, R.W. 1977. "Combustion of Bagasse: Literature Review." Sugar Technology Reviews, vol. 4 no. 2 May 1977. pp 89-130

Lambert, M.J. 1976. "Preparation of Plant Material for

Estimating a Wide Range of Elements." Forestry Commission of New South Wales, Research Note No. 29

Ode, W.H. 1963. "Coal Analysis and Mineral Matter." Chap 5 in Chemistry of Coal Utilization - Supp. Vol. Lowry, H.H. Ed. John Wiley & Sons. pp 202-231

Levin, E.M., Robbins, C.R., McMurdie, H.F. 1974. "Phase Diagrams for Ceramists." 3rd Ed. Publ. by The American Ceramic Society

Medlin, J.H., Suhr, N.H., Bodkin, J.B. 1969. "Atomic Absorption Analysis of Silicates Emplying $LiBO_2$ Fusion." Atomic Absorption Newsletter, vol. 8 no. 2, March-April 1969. pp 25-29

Muter, R.B., Cockrell, C.F. 1969. "The Analysis of Sodium, Potassium, Calcium and Magnesium in Siliceous Coal Ash and Related Materials by Atomic Absorption Spectroscopy." Applied Septroscopy vol. 23 no. 5, Sept./Oct. 1969. pp 493-496

Muter, R.B., Nice, L.L. 1975. "Major and Minor Constituents in Siliceous Materials by Atomic Absorption Spectroscopy." Advances in Chemistry Series 141, Trace Elements in Fuel. Babu, S.P. Ed. Symposium spons. by Division of Fuel Chemistry, at American Chemical Society Meeting, Chicago, Illinois, August 30, 1973. pp 57-65

Ness, H.M., Honea, F.I., Schanilec, F.L. 1979. "Combustion of Sunflower Hulls with Lignite: Results of Pilot Plant and Field Tests." United States Dept. of Energy, Grand Forks Energy Technical Center, Grand Forks, North Dakota. Dec. 19,1979

Prasad, M., Spiers, M. 1978. "Comparative Study of Ashing Techniques for the Digestion of Horticultural Plant Samples." Journal of Agriculture and Food Chemistry, vol. 26, no. 4, July/August 1978. pp 824-827

Reason, J. 1983. "Utilities Turn to Wood as a Fuel Source." Power, Jan. 1983

Sage, W.L., McIlroy 1960. "Relationship of Coal Ash Viscosity to Chemical Composition." Journal of Engineering for Power, April 1960. pp 145-155

Sanyal, A., Williamson, J. 1981. "Slagging in Boiler Furnaces: an Assessment Technique Based on Thermal Behavior of Coal Minerals." Journal of the Institute of Energy, vol 54, no. 420, September 1981. pp 158-162

Sehgal, R.S., Wong, B. 1974. "Significance of Calorific Value, Ultimate Analysis, Ash Fusion and Mineral Analysis of Ash." Symposium on Coal Evaluation, Oct. 31 - Nov. 1, 1974, Calgary, Alberta. Spons: Alberta Research Council and the Coal Association of Canada. pp 21-30

Shapiro, L., Brannock, W.W. 1956. "Rapid Analysis of Silicate Rocks." U.S. Geological Survey Bulletin 1036-C

Singh, A.P., Sabharwal, V.P., Biswas, S.C. 1980. "A Study on Fusion Behavior of Coal Ashes for Gasification of Coal." Fertilizer Technology, vol. 17, no. 1 & 2, 1980. pp 19-23

Skoog, D.A., West, D.M. 1976. "Preliminary Steps to an Analyses." Chap 27 in Fundamentals of Analytical Chemistry. 3rd Ed. Holt, Rinehart and Winston. pp 593-605

Sondreal, E.A., Ellman, R.C. 1975. "Fusibility of Ash from Lignite and Its Correlation with Ash Compostion." United States Bureau of Mines, Report of Investigation #GERFC/RI-75-1

Tillman, D.A. 1978. "Wood as an Energy Resource." Academic Press

Vaninetti, G.E., Busch, C.F. 1982. "Mineral Analysis of Ash Data a Utility Perspective." Coal Quality, Spring 1982. pp 22-31

Volborth, A. 1979. "Problems of Oxygen Stoichiometry in Analyses of Coal and Related Materials." Chap. 55 in Analytical Methods for Coal and Coal Products, vol. 3. Ed. Karr, C. Jr. Academic Press

Watling, H.R., Wardale, I.M. 1977. "Comparison of Wet and Dry Ashing for the Analysis of Biological Materials by Atomic Absorption Spectroscopy." The Analysis of Biological Materials, Butler, L.R.P. Ed. Proceedings of a Conference held in Pretoria, South Africa, Oct. 1977. Spons. by: The Spectroscopic Society of South Africa

Williams, R.O., Horsfield, B. 1977. "Generation of Low-BTU Fuel Gas from Agricultural Residues Experiments with a Laboratory-Scale Gas Producer." in Food, Fertilizer and Agricultural Residues, Proc. of the 1977 Cornell Agriculture Waste Management Conference, ed. Loehr, R.C.

Ann Arbor Science.

Williams, R.O, Goss, J.R., Mehlschau, J.J., Jenkins, B., Ramming, J. 1978. "Development of Pilot Plant Gasification Systems for the Conversion of Crop and Wood Residues to thermal and Electical Energy." in Solid Wastes and Residues: Conversion by Advanced Thermal Processes, American Chemical Society Symposium #76, ed. Jones, J.L., Radding, S.B., 1978. pp 142-162

Williams, R.O., Goss, J.R. 1977. "An Assessment of the Gasification Characterisitics of Some Agricultural and Forest Industry Residues Using a Laboratory Gasifier." Resource, Recovery and Conservation, vol.3, 1979. pp 317-329

Winegartner, E.C., Rhodes, B.T. 1975. "An Empirical Study of the Relation of Chemical Properties to Ash Fusion Temperatures." Journal of Engineering for Power, vol 97, July 1975. pp 395-406

Zsuffa, L. 1982. "The Production of Wood for Energy." in Energy from Forest Biomass, Smith, W.R. Ed. Academic Press. pp 5-17

1951. "Peat, Wood, Wood Wastes, Charcoal and Agricultural Wastes." Chap 5 in Fuels and Combustion Handbook. 1st Ed. Ed. Johnson, A. J., McGraw-Hill. pp 105-128

1981. "Handbook of Chemistry and Physics." 61st Ed., CRC Press Inc.

APPENDIX A

Fuel Analyses Tables

Proximate Values - Wet Basis

Sample	Trial	% Moist	% Vol	% Fixd C	% Ash
* Category: AG WASTES					
BARLEY STRAW	1	6.980	73.220	13.770	6.020
BARLEY STRAW	2	6.590	71.110	16.530	5.770
BARLEY STRAW	3	6.100	75.860	12.750	5.300
BARLEY STRAW	4	6.000	77.960	10.400	5.650
BARLEY STRAW	5	5.860	76.690	11.590	5.860
BARLEY STRAW	6	6.970	75.500	10.550	6.970
BARLEY STRAW	7	6.640	73.250	13.690	6.430
CORN COBS	1	16.080	68.010	14.500	1.410
CORN COBS	2	15.890	69.980	12.550	1.570
CORN COBS	3	24.440	60.810	13.470	1.280
CORN COBS	4	14.800	72.720	11.220	1.250
CORN COBS	5	13.420	72.090	13.010	1.480
CORN COBS	6	13.320	73.370	11.620	1.680
CORN COBS	7	28.240	59.920	11.470	0.370
CORN COBS	8	27.640	59.700	12.630	0.030
CORN COBS	9	33.330	59.550	6.510	0.620
COTTON GIN TRASH	1	8.840	67.600	15.970	7.580
COTTON GIN TRASH	2	9.430	66.360	15.960	8.250
COTTON GIN TRASH	3	6.970	72.560	11.980	8.490
COTTON GIN TRASH	4	7.110	73.710	10.240	8.940
COTTON GIN TRASH	5	6.850	73.010	11.150	8.990
COTTON GIN TRASH	6	6.750	73.210	11.410	8.630
COTTON GIN TRASH	7	6.480	74.550	9.960	9.000
PEANUT HULLS	1	8.058	73.826	16.672	1.445
PEANUT HULLS	2	8.205	75.384	14.985	1.426
PEANUT HULLS	3	7.993	76.470	14.441	1.096
RICE HULLS	1	8.043	59.397	13.388	19.173
RICE HULLS	2	7.872	59.000	12.113	21.015
RICE HULLS	3	7.697	60.101	13.246	18.956
RICE STRAW	1	5.990	62.590	13.720	17.670
RICE STRAW	2	6.050	62.880	13.360	17.700
RICE STRAW	3	6.240	61.730	12.540	19.490
RICE STRAW	4	6.340	61.960	14.340	17.350
RICE STRAW	5	6.370	61.690	13.890	18.040
RICE STRAW	6	6.570	62.200	13.240	18.000
SUGAR CANE BAGASSE	1	6.971	82.306	8.234	2.489
SUGAR CANE BAGASSE	2	7.010	81.012	10.401	1.577
SUGAR CANE BAGASSE	3	6.912	83.640	8.190	1.259
WALNUT SHELLS	1	10.350	66.920	20.130	2.610
WALNUT SHELLS	2	10.440	66.360	20.790	2.420
WALNUT SHELLS	3	10.540	68.430	19.460	1.570
WHEAT STRAW	1	7.123	76.539	10.656	5.683
WHEAT STRAW	2	6.500	75.745	12.442	5.313
WHEAT STRAW	3	6.483	76.918	11.555	5.045

Proximate Values - Wet Basis

Sample	Trial	% Moist	% Vol	% Fixd C	% Ash
* Category: WOOD					
FIR BARK	1	24.250	58.930	16.070	0.750
FIR BARK	2	22.630	60.560	16.380	0.730
FIR BARK	3	23.180	61.250	14.230	1.330
FIR BARK	4	22.320	59.550	17.480	0.640
MIXED HARDWOOD	1	23.000	68.000	7.000	2.000
MIXED HARDWOOD	2	20.250	70.690	8.550	0.510
MIXED HARDWOOD	3	24.430	67.940	6.830	0.790
PINE WEE CHIPS	1	5.975	81.576	12.094	0.355
PINE WEE CHIPS	2	6.008	82.364	11.370	0.259
PINE WEE CHIPS	3	5.848	81.960	11.838	0.354
REDWOOD BARK	1	20.960	60.860	17.790	0.380
REDWOOD BARK	2	21.290	61.120	17.370	0.220
REDWOOD BARK	3	22.660	58.680	18.460	0.190
REDWOOD BARK	4	20.930	59.850	19.010	0.210
REDWOOD BARK	5	19.460	65.640	13.340	1.550
REDWOOD BARK	6	19.530	60.380	17.220	2.870
REDWOOD BARK	7	19.490	63.360	16.180	0.970
REDWOOD BARK	8	19.660	62.390	16.520	1.430
REDWOOD BARK	9	19.650	63.710	15.640	1.000
REDWOOD BARK	10	19.740	64.200	15.350	0.710
REDWOOD SAWDUST	1	56.870	35.900	7.000	0.230
REDWOOD SAWDUST	2	57.360	35.850	6.660	0.140
REDWOOD SAWDUST	3	53.990	38.270	7.640	0.100
REDWOOD SAWDUST	4	57.900	35.980	5.890	0.230
REDWOOD SAWDUST	5	57.900	35.980	5.890	0.230
TREE CHIPS - S. CAROLINA	1	6.736	77.605	14.604	1.056
TREE CHIPS - S. CAROLINA	2	6.518	78.122	14.549	0.811
TREE CHIPS - S. CAROLINA	3	6.394	78.311	14.611	0.683

Proximate Values - Dry Basis

Sample	Trial	% Vol	% Fixd C	% Ash
* Category: AG WASTES				
BARLEY STRAW	1	78.722	14.804	6.472
BARLEY STRAW	2	76.126	17.696	6.177
BARLEY STRAW	3	80.779	13.576	5.643
BARLEY STRAW	4	82.927	11.062	6.009
BARLEY STRAW	5	81.463	12.311	6.224
BARLEY STRAW	6	81.165	11.341	7.493
BARLEY STRAW	7	78.451	14.662	6.886
CORN COBS	1	81.041	17.278	1.680
CORN COBS	2	83.210	14.922	1.866
CORN COBS	3	80.479	17.826	1.694
CORN COBS	4	85.362	13.170	1.467
CORN COBS	5	83.264	15.026	1.709
CORN COBS	6	84.654	13.407	1.938
CORN COBS	7	83.500	15.983	0.515
CORN COBS	8	82.504	17.454	0.041
CORN COBS	9	89.299	9.770	0.930
COTTON GIN TRASH	1	74.163	17.520	8.315
COTTON GIN TRASH	2	73.269	17.621	9.108
COTTON GIN TRASH	3	77.996	12.877	9.126
COTTON GIN TRASH	4	79.351	11.023	9.624
COTTON GIN TRASH	5	78.378	11.969	9.651
COTTON GIN TRASH	6	78.509	12.235	9.254
COTTON GIN TRASH	7	79.724	10.651	9.624
PEANUT HULLS	1	80.295	18.132	1.571
PEANUT HULLS	2	82.122	16.324	1.553
PEANUT HULLS	3	83.113	15.695	1.191
RICE HULLS	1	64.591	14.558	20.849
RICE HULLS	2	64.041	13.148	22.810
RICE HULLS	3	65.112	14.350	20.536
RICE STRAW	1	66.599	14.598	18.801
RICE STRAW	2	66.936	14.221	18.841
RICE STRAW	3	65.838	13.374	20.787
RICE STRAW	4	66.161	15.312	18.526
RICE STRAW	5	65.894	14.836	19.269
RICE STRAW	6	66.566	14.169	19.263
SUGAR CANE BAGASSE	1	88.473	8.851	2.675
SUGAR CANE BAGASSE	2	87.119	11.185	1.695
SUGAR CANE BAGASSE	3	89.849	8.798	1.352
WALNUT SHELLS	1	74.637	22.451	2.910
WALNUT SHELLS	2	74.087	23.210	2.701
WALNUT SHELLS	3	76.492	21.752	1.754
WHEAT STRAW	1	82.408	11.473	6.118
WHEAT STRAW	2	81.010	13.306	5.682
WHEAT STRAW	3	82.249	12.355	5.394

Proximate Values - Dry Basis

Sample	Trial	% Vol	% Fixd C	% Ash
* Category: WOOD				
FIR BARK	1	77.795	21.214	0.990
FIR BARK	2	77.970	21.089	0.939
FIR BARK	3	79.742	18.526	1.731
FIR BARK	4	76.670	22.505	0.823
MIXED HARDWOOD	1	88.311	9.090	2.597
MIXED HARDWOOD	2	88.639	10.721	0.639
MIXED HARDWOOD	3	89.915	9.039	1.045
PINE WEE CHIPS	1	86.759	12.862	0.377
PINE WEE CHIPS	2	87.627	12.096	0.275
PINE WEE CHIPS	3	87.050	12.573	0.375
REDWOOD BARK	1	77.008	22.510	0.480
REDWOOD BARK	2	77.652	22.068	0.279
REDWOOD BARK	3	75.882	23.871	0.245
REDWOOD BARK	4	75.692	24.041	0.265
REDWOOD BARK	5	81.509	16.565	1.924
REDWOOD BARK	6	75.034	21.399	3.566
REDWOOD BARK	7	78.698	20.096	1.204
REDWOOD BARK	8	77.657	20.562	1.779
REDWOOD BARK	9	79.290	19.464	1.244
REDWOOD BARK	10	79.990	19.125	0.884
REDWOOD SAWDUST	1	83.236	16.230	0.533
REDWOOD SAWDUST	2	84.056	15.615	0.328
REDWOOD SAWDUST	3	83.177	16.605	0.217
REDWOOD SAWDUST	4	85.463	13.990	0.546
REDWOOD SAWDUST	5	85.463	13.990	0.546
TREE CHIPS - S. CAROLINA	1	83.209	15.658	1.132
TREE CHIPS - S. CAROLINA	2	83.569	15.563	0.867
TREE CHIPS - S. CAROLINA	3	83.661	15.609	0.729

Proximate Values - Dry Ash Free Basis

Sample	Trial	% Vol	% Fixd C
* Category: AG WASTES			
BARLEY STRAW	1	84.170	15.829
BARLEY STRAW	2	81.138	18.861
BARLEY STRAW	3	85.611	14.388
BARLEY STRAW	4	88.229	11.770
BARLEY STRAW	5	86.871	13.128
BARLEY STRAW	6	87.739	12.260
BARLEY STRAW	7	84.253	15.746
CORN COBS	1	82.426	17.573
CORN COBS	2	84.793	15.206
CORN COBS	3	81.865	18.134
CORN COBS	4	86.633	13.366
CORN COBS	5	84.712	15.287
CORN COBS	6	86.327	13.672
CORN COBS	7	83.933	16.066
CORN COBS	8	82.538	17.461
CORN COBS	9	90.137	9.862
COTTON GIN TRASH	1	80.890	19.109
COTTON GIN TRASH	2	80.612	19.387
COTTON GIN TRASH	3	85.829	14.170
COTTON GIN TRASH	4	87.802	12.197
COTTON GIN TRASH	5	86.751	13.248
COTTON GIN TRASH	6	86.516	13.483
COTTON GIN TRASH	7	88.214	11.785
PEANUT HULLS	1	81.577	18.422
PEANUT HULLS	2	83.417	16.582
PEANUT HULLS	3	84.115	15.884
RICE HULLS	1	81.606	18.393
RICE HULLS	2	82.966	17.033
RICE HULLS	3	81.940	18.059
RICE STRAW	1	82.020	17.979
RICE STRAW	2	82.476	17.523
RICE STRAW	3	83.115	16.884
RICE STRAW	4	81.205	18.794
RICE STRAW	5	81.622	18.377
RICE STRAW	6	82.449	17.550
SUGAR CANE BAGASSE	1	90.905	9.094
SUGAR CANE BAGASSE	2	88.621	11.378
SUGAR CANE BAGASSE	3	91.081	8.918
WALNUT SHELLS	1	76.875	23.124
WALNUT SHELLS	2	76.144	23.855
WALNUT SHELLS	3	77.858	22.141
WHEAT STRAW	1	87.779	12.220
WHEAT STRAW	2	85.891	14.108
WHEAT STRAW	3	86.939	13.060

Proximate Values - Dry Ash Free Basis

Sample	Trial	% Vol	% Fixd C
* Category: WOOD			
FIR BARK	1	78.573	21.426
FIR BARK	2	78.710	21.289
FIR BARK	3	81.147	18.852
FIR BARK	4	77.307	22.692
MIXED HARDWOOD	1	90.666	9.333
MIXED HARDWOOD	2	89.209	10.790
MIXED HARDWOOD	3	90.865	9.134
PINE WEE CHIPS	1	87.088	12.911
PINE WEE CHIPS	2	87.869	12.130
PINE WEE CHIPS	3	87.379	12.620
REDWOOD BARK	1	77.380	22.619
REDWOOD BARK	2	77.869	22.130
REDWOOD BARK	3	76.069	23.930
REDWOOD BARK	4	75.893	24.106
REDWOOD BARK	5	83.109	16.890
REDWOOD BARK	6	77.809	22.190
REDWOOD BARK	7	79.658	20.341
REDWOOD BARK	8	79.064	20.935
REDWOOD BARK	9	80.289	19.710
REDWOOD BARK	10	80.703	19.296
REDWOOD SAWDUST	1	83.682	16.317
REDWOOD SAWDUST	2	84.333	15.666
REDWOOD SAWDUST	3	83.358	16.641
REDWOOD SAWDUST	4	85.932	14.067
REDWOOD SAWDUST	5	85.932	14.067
TREE CHIPS - S. CAROLINA	1	84.162	15.837
TREE CHIPS - S. CAROLINA	2	84.300	15.699
TREE CHIPS - S. CAROLINA	3	84.276	15.723

Ultimate Values - Dry Basis

Sample	Trial	% C	% H	% O	% Ash
* Category: AG WASTES					
BARLEY STRAW	1	43.681	6.361	43.647	6.310
BARLEY STRAW	2	46.072	5.725	42.026	6.175
BARLEY STRAW	3	44.678	5.930	42.061	7.330
BARLEY STRAW	4	44.998	6.068	41.848	7.083
BARLEY STRAW	5	35.671	5.501	52.577	6.250
BARLEY STRAW	6	37.730	5.432	49.850	6.987
BARLEY STRAW	7	43.437	5.710	44.099	6.752
CORN COBS	1	48.464	7.041	43.417	1.076
CORN COBS	2	42.015	5.888	50.213	1.882
CORN COBS	3	47.956	6.199	44.028	1.815
CORN COBS	4	46.366	4.834	47.115	1.682
CORN COBS	5	47.573	4.767	46.005	1.654
CORN COBS	6	42.160	5.973	50.067	1.798
COTTON GIN TRASH	1	43.241	5.372	44.163	7.222
COTTON GIN TRASH	2	44.137	5.581	42.084	8.196
COTTON GIN TRASH	3	45.402	5.628	41.927	7.040
PEANUT HULLS	1	51.999	6.890	39.112	1.996
PEANUT HULLS	2	50.065	6.055	41.877	2.000
PEANUT HULLS	3	49.118	5.944	42.736	2.200
RICE HULLS	1	37.977	4.951	36.549	20.522
RICE HULLS	2	37.619	4.944	36.156	21.279
RICE STRAW	1	38.339	4.993	38.209	18.457
RICE STRAW	2	38.243	5.098	38.851	17.806
RICE STRAW	3	38.090	6.244	38.735	16.929
RICE STRAW	4	38.127	5.452	38.844	17.575
RICE STRAW	5	37.772	5.011	39.564	17.651
SUGAR CANE BAGASSE	1	42.163	5.497	50.502	1.836
SUGAR CANE BAGASSE	2	47.182	5.258	46.828	0.729
SUGAR CANE BAGASSE	3	47.013	5.873	45.967	1.145
SUGAR CANE BAGASSE	4	47.594	5.874	44.510	2.019
SUGAR CANE BAGASSE	5	49.088	6.436	43.075	1.399
WALNUT SHELLS	1	49.130	6.070	43.250	1.550
WALNUT SHELLS	2	48.940	5.980	44.160	0.910
WHEAT STRAW	1	46.548	6.297	41.951	5.201
WHEAT STRAW	2	46.157	6.325	41.557	5.959

Ultimate Values - Dry Basis

Sample	Trial	% C	% H	% O	% Ash
* Category: WOOD					
FIR BARK	1	49.588	5.951	43.702	0.757
FIR BARK	2	54.648	5.925	38.568	0.856
FIR BARK	3	54.923	5.664	38.664	0.747
FIR BARK	4	55.247	6.234	37.719	0.798
FIR BARK	5	59.763	9.191	29.840	1.204
MIXED HARDWOOD	1	48.517	6.058	44.719	0.703
MIXED HARDWOOD	2	48.893	6.069	44.373	0.663
PINE WEE CHIPS	1	50.041	6.247	43.295	0.415
PINE WEE CHIPS	2	51.240	6.331	41.981	0.445
PINE WEE CHIPS	3	50.569	6.208	42.831	0.391
REDWOOD BARK	1	50.594	5.592	43.655	0.157
REDWOOD BARK	2	51.091	5.366	43.370	0.171
REDWOOD BARK	3	55.137	5.889	38.634	0.338
REDWOOD BARK	4	51.698	5.275	42.506	0.519
REDWOOD BARK	5	50.367	5.151	42.576	1.903
REDWOOD SAWDUST	1	52.554	6.496	40.629	0.319
REDWOOD SAWDUST	2	54.013	6.249	39.360	0.376
REDWOOD SAWDUST	3	51.868	5.918	42.085	0.127
TREE CHIPS - S. CAROLINA	1	50.343	6.230	42.620	0.805
TREE CHIPS - S. CAROLINA	2	49.542	5.745	43.800	0.911

Ultimate Values - Dry Ash Free Basis

Sample	Trial	% C	% H	% O
* Category: AG WASTES				
BARLEY STRAW	1	46.623	6.789	46.586
BARLEY STRAW	2	49.104	6.102	44.792
BARLEY STRAW	3	48.212	6.399	45.388
BARLEY STRAW	4	48.429	6.531	45.038
BARLEY STRAW	5	38.049	5.867	56.082
BARLEY STRAW	6	40.564	5.840	53.595
BARLEY STRAW	7	46.583	6.123	47.292
CORN COBS	1	48.991	7.118	43.889
CORN COBS	2	42.821	6.001	51.176
CORN COBS	3	48.843	6.314	44.842
CORN COBS	4	47.159	4.917	47.922
CORN COBS	5	48.373	4.847	46.778
CORN COBS	6	42.932	6.083	50.984
COTTON GIN TRASH	1	46.607	5.790	47.601
COTTON GIN TRASH	2	48.078	6.080	45.841
COTTON GIN TRASH	3	48.841	6.054	45.103
PEANUT HULLS	1	53.059	7.031	39.909
PEANUT HULLS	2	51.088	6.179	42.732
PEANUT HULLS	3	50.223	6.078	43.698
RICE HULLS	1	47.783	6.230	45.986
RICE HULLS	2	47.789	6.280	45.930
RICE STRAW	1	47.017	6.124	46.858
RICE STRAW	2	46.528	6.202	47.268
RICE STRAW	3	45.852	7.517	46.629
RICE STRAW	4	46.257	6.614	47.127
RICE STRAW	5	45.869	6.085	48.045
SUGAR CANE BAGASSE	1	42.952	5.600	51.447
SUGAR CANE BAGASSE	2	47.529	5.297	47.173
SUGAR CANE BAGASSE	3	47.558	5.941	46.500
SUGAR CANE BAGASSE	4	48.575	5.996	45.428
SUGAR CANE BAGASSE	5	49.785	6.527	43.687
WALNUT SHELLS	1	49.904	6.166	43.931
WALNUT SHELLS	2	49.394	6.036	44.570
WHEAT STRAW	1	49.103	6.643	44.253
WHEAT STRAW	2	49.082	6.726	44.191

Ultimate Values - Dry Ash Free Basis

Sample	Trial	% C	% H	% O
* Category: WOOD				
FIR BARK	1	49.966	5.997	44.036
FIR BARK	2	55.120	5.976	38.902
FIR BARK	3	55.337	5.707	38.955
FIR BARK	4	55.692	6.284	38.023
FIR BARK	5	60.491	9.303	30.204
MIXED HARDWOOD	1	48.861	6.101	45.036
MIXED HARDWOOD	2	49.219	6.109	44.670
PINE WEE CHIPS	1	50.250	6.273	43.476
PINE WEE CHIPS	2	51.469	6.360	42.169
PINE WEE CHIPS	3	50.767	6.232	42.999
REDWOOD BARK	1	50.674	5.601	43.724
REDWOOD BARK	2	51.179	5.375	43.445
REDWOOD BARK	3	55.325	5.909	38.765
REDWOOD BARK	4	51.968	5.302	42.728
REDWOOD BARK	5	51.345	5.251	43.402
REDWOOD SAWDUST	1	52.722	6.517	40.759
REDWOOD SAWDUST	2	54.217	6.273	39.509
REDWOOD SAWDUST	3	51.934	5.926	42.139
TREE CHIPS - S. CAROLINA	1	50.751	6.281	42.966
TREE CHIPS - S. CAROLINA	2	49.998	5.797	44.203

Ultimate Values - IGT Equation Calculated

Sample	Trial	HHV IGT cal/gm	HHV IGT Btu/lbm
* Category: AG WASTES			
BARLEY STRAW	1	4294.55	7730.20
BARLEY STRAW	2	4335.44	7803.79
BARLEY STRAW	3	4281.38	7706.50
BARLEY STRAW	4	4358.22	7844.81
BARLEY STRAW	5	3115.17	5607.30
BARLEY STRAW	6	3336.42	6005.55
BARLEY STRAW	7	4054.54	7298.18
CORN COBS	1	4924.91	8864.84
CORN COBS	2	3837.90	6908.23
CORN COBS	3	4597.12	8274.82
CORN COBS	4	3948.54	7107.38
CORN COBS	5	4057.41	7303.34
CORN COBS	6	3880.99	6985.78
COTTON GIN TRASH	1	3928.20	7070.76
COTTON GIN TRASH	2	4123.37	7422.08
COTTON GIN TRASH	3	4249.81	7649.66
PEANUT HULLS	1	5284.85	9512.74
PEANUT HULLS	2	4784.30	8611.74
PEANUT HULLS	3	4646.85	8364.34
RICE HULLS	1	3535.97	6364.75
RICE HULLS	2	3512.92	6323.25
RICE STRAW	1	3538.78	6369.81
RICE STRAW	2	3547.92	6386.25
RICE STRAW	3	3904.34	7027.82
RICE STRAW	4	3651.43	6572.57
RICE STRAW	5	3462.35	6232.24
SUGAR CANE BAGASSE	1	3718.31	6692.97
SUGAR CANE BAGASSE	2	4160.69	7489.25
SUGAR CANE BAGASSE	3	4364.33	7855.79
SUGAR CANE BAGASSE	4	4450.59	8011.06
SUGAR CANE BAGASSE	5	4792.92	8627.26
WALNUT SHELLS	1	4676.00	8416.80
WALNUT SHELLS	2	4606.00	8290.80
WHEAT STRAW	1	4560.70	8209.26
WHEAT STRAW	2	4546.03	8182.86

Ultimate Values - IGT Equation Calculated

Sample	Trial	HHV IGT cal/gm	HHV IGT Btu/lbm
* Category: WOOD			
FIR BARK	1	4664.94	8396.90
FIR BARK	2	5215.38	9387.68
FIR BARK	3	5152.98	9275.37
FIR BARK	4	5386.24	9695.24
FIR BARK	5	6912.59	12442.66
MIXED HARDWOOD	1	4582.54	8248.57
MIXED HARDWOOD	2	4626.55	8327.79
PINE WEE CHIPS	1	4808.15	8654.68
PINE WEE CHIPS	2	4969.99	8945.98
PINE WEE CHIPS	3	4852.12	8733.81
REDWOOD BARK	1	4637.03	8346.65
REDWOOD BARK	2	4613.90	8305.02
REDWOOD BARK	3	5243.83	9438.89
REDWOOD BARK	4	4658.07	8384.53
REDWOOD BARK	5	4503.76	8106.77
REDWOOD SAWDUST	1	5168.21	9302.78
REDWOOD SAWDUST	2	5245.23	9441.42
REDWOOD SAWDUST	3	4888.75	8799.75
TREE CHIPS - S. CAROLINA	1	4845.39	8721.70
TREE CHIPS - S. CAROLINA	2	4592.52	8266.54

Higher Heating Values

Sample	Trial	HHV cal/gm	HHV Btu/lbm
* Category: AG WASTES			
BARLEY STRAW	1	3942.00	7095.60
BARLEY STRAW	2	4850.00	8730.00
BARLEY STRAW	3	3317.00	5970.60
BARLEY STRAW	4	4312.00	7761.60
BARLEY STRAW	5	4240.00	7632.00
CORN COBS	1	4425.00	7965.00
CORN COBS	2	4584.00	8251.20
CORN COBS	3	4473.00	8051.40
CORN COBS	4	4405.00	7929.00
CORN COBS	5	4482.00	8067.60
CORN COBS	6	4393.07	7907.52
CORN COBS	7	4378.68	7881.62
COTTON GIN TRASH	1	4035.00	7263.00
COTTON GIN TRASH	2	4308.00	7754.40
COTTON GIN TRASH	3	4058.00	7304.40
PEANUT HULLS	1	4831.73	8697.11
PEANUT HULLS	2	4798.34	8637.01
RICE HULLS	1	3699.13	6658.43
RICE HULLS	2	4242.09	7635.76
RICE HULLS	3	3536.75	6366.15
RICE STRAW	1	2573.00	4631.40
RICE STRAW	2	3089.00	5560.20
RICE STRAW	3	3598.00	6476.40
RICE STRAW	4	3486.00	6274.80
RICE STRAW	5	3394.17	6109.50
RICE STRAW	6	3738.28	6728.90
RICE STRAW	7	3801.71	6843.07
SUGAR CANE BAGASSE	1	4702.57	8464.62
SUGAR CANE BAGASSE	2	4898.95	8818.11
SUGAR CANE BAGASSE	3	5077.03	9138.65
SUGAR CANE BAGASSE	4	5271.45	9488.61
WALNUT SHELLS	1	4953.10	8915.58
WALNUT SHELLS	2	4613.03	8303.45
WALNUT SHELLS	3	5179.83	9323.69
WHEAT STRAW	1	4612.12	8301.81
WHEAT STRAW	2	4401.39	7922.50

Higher Heating Values

Sample	Trial	HHV cal/gm	HHV Btu/lbm
* Category: WOOD			
FIR BARK	1	5231.14	9416.05
FIR BARK	2	5318.78	9573.80
FIR BARK	3	5526.96	9948.52
MIXED HARDWOOD	1	4479.00	8062.20
MIXED HARDWOOD	2	4582.00	8247.60
MIXED HARDWOOD	3	4497.00	8094.60
MIXED HARDWOOD	4	4265.00	7677.00
PINE WEE CHIPS	1	4836.01	8704.81
PINE WEE CHIPS	2	5337.89	9608.20
PINE WEE CHIPS	3	4654.07	8377.32
PINE WEE CHIPS	4	4921.99	8859.58
REDWOOD BARK	1	4261.00	7669.80
REDWOOD BARK	2	5486.28	9875.30
REDWOOD BARK	3	4951.17	8912.10
REDWOOD SAWDUST	1	5014.60	9026.28
REDWOOD SAWDUST	2	4222.36	7600.24
REDWOOD SAWDUST	3	5179.27	9322.68
REDWOOD SAWDUST	4	5978.85	10761.93
TREE CHIPS - S. CAROLINA	1	4855.03	8739.05
TREE CHIPS - S. CAROLINA	2	5324.36	9583.84
TREE CHIPS - S. CAROLINA	3	5119.83	9215.69

APPENDIX B

Coal Correlations and Ratios

Barley Straw

ELEMENTAL ANALYSIS OF ASH (%)

SIO2	35.83
AL2O3	1.40
TIO2	0.26
FE2O3	0.83
CAO	5.90
MGO	1.59
NA2O	1.42
K2O	37.95
P2O5	5.83
SO3	<0.01
TOTAL	91.01

ASH FUSION TEMPERATURES (DEG F)

	OXIDIZING ATMOSPHERE	REDUCING ATMOSPHERE
INITIAL	ND **	1590
SOFTENING		1625
HEMISPHERICAL		2010
FLUID		2240

ASH VISCOSITY CALCULATIONS *

BASE CONTENT (%)	55.99
ACID CONTENT (%)	44.01
DOLOMITE RATIO	15.71
BASE/ACID RATIO	1.27
SILICA/ALUMINA RATIO	25.59
T(CV),DEG F	ND **
T250 TEMPERATURE (DEG F)	OTL **
EQUIV SILICA CONTENT (%)	81.16
VISCOSITY FROM EQUIV SILICA (POISE),2600 F	>999.99
ASH TYPE	LIGNITE

% MnO = 0.07

* 'FUSIBILITY-VISCOSITY OF LIGNITE-TYPE ASH'. A.F. DUZY,1965.
'RELATIONSHIP OF COAL-ASH VISCOSITY TO CHEMICAL COMPOSTION'.
W.L. SAGE AND J.B. MCILROY,1960.

** OTL=OUTSIDE TABLE LIMITS. ND=NOT DETERMINED.

Corn Cobs

ELEMENTAL ANALYSIS OF ASH (%)

SIO2	28.24
AL2O3	0.46
TIO2	0.05
FE2O3	0.70
CAO	0.30
MGO	3.58
NA2O	1.25
K2O	39.16
P2O5	11.87
SO3	<0.01
TOTAL	85.61

ASH FUSION TEMPERATURES (DEG F)

	OXIDIZING ATMOSPHERE	REDUCING ATMOSPHERE
INITIAL	ND **	1595
SOFTENING		1614
HEMISPHERICAL		1905
FLUID		2000

ASH VISCOSITY CALCULATIONS *

BASE CONTENT (%)	61.01
ACID CONTENT (%)	38.99
DOLOMITE RATIO	8.62
BASE/ACID RATIO	1.56
SILICA/ALUMINA RATIO	61.39
T(CV),DEG F	ND **
T250 TEMPERATURE (DEG F)	OTL **
EQUIV SILICA CONTENT (%)	86.05
VISCOSITY FROM EQUIV SILICA (POISE),2600 F	>999.99
ASH TYPE	LIGNITE

% MnO = 0.05

* 'FUSIBILITY-VISCOSITY OF LIGNITE-TYPE ASH'. A.F. DUZY,1965.
'RELATIONSHIP OF COAL-ASH VISCOSITY TO CHEMICAL COMPOSTION'.
W.L. SAGE AND J.B. MCILROY,1960.

** OTL=OUTSIDE TABLE LIMITS. ND=NOT DETERMINED.

Cotton Gin Trash

ELEMENTAL ANALYSIS OF ASH (%)

SIO2	32.06
AL2O3	5.42
TIO2	0.38
FE2O3	1.86
CAO	13.91
MGO	3.65
NA2O	1.96
K2O	24.08
P2O5	8.61
SO3	<0.01
TOTAL	91.93

ASH FUSION TEMPERATURES (DEG F)

	OXIDIZING ATMOSPHERE	REDUCING ATMOSPHERE
INITIAL	ND **	2205
SOFTENING		2245
HEMISPHERICAL		2372
FLUID		2445

ASH VISCOSITY CALCULATIONS *

BASE CONTENT (%)	54.56
ACID CONTENT (%)	45.44
DOLOMITE RATIO	38.63
BASE/ACID RATIO	1.20
SILICA/ALUMINA RATIO	5.92
T(CV),DEG F	ND **
T250 TEMPERATURE (DEG F)	OTL **
EQUIV SILICA CONTENT (%)	62.28
VISCOSITY FROM EQUIV SILICA (POISE),2600 F	46.54
ASH TYPE	LIGNITE

% MnO = 0.07

* 'FUSIBILITY-VISCOSITY OF LIGNITE-TYPE ASH'. A.F. DUZY,1965.
'RELATIONSHIP OF COAL-ASH VISCOSITY TO CHEMICAL COMPOSTION'.
W.L. SAGE AND J.B. MCILROY,1960.

** OTL=OUTSIDE TABLE LIMITS. ND=NOT DETERMINED.

Peanut Hulls

```
ELEMENTAL ANALYSIS OF ASH (%)           ASH FUSION TEMPERATURES (DEG F)
-----------------------------           -------------------------------

      SIO2       12.49                              OXIDIZING       REDUCING
      AL2O3       2.68                              ATMOSPHERE     ATMOSPHERE
      TIO2        0.19
      FE2O3       1.07        INITIAL                  ND **          2285
      CAO         5.05        SOFTENING                               2330
      MGO         3.88        HEMISPHERICAL                           2350
      NA2O        2.65        FLUID                                   2390
      K2O        35.38
      P2O5       13.80
      SO3        <0.01
                 ------
      TOTAL      77.19

ASH VISCOSITY CALCULATIONS *
----------------------------
      BASE CONTENT (%)           75.77
      ACID CONTENT (%)           24.23
      DOLOMITE RATIO             18.59
      BASE/ACID RATIO             3.13
      SILICA/ALUMINA RATIO        4.66
      T(CV),DEG F                ND **
      T250 TEMPERATURE (DEG F)  OTL **
      EQUIV SILICA CONTENT (%)   55.54
      VISCOSITY FROM EQUIV
         SILICA (POISE),2600 F   17.61
      ASH TYPE                  LIGNITE
```

% MnO = 0.29

```
* 'FUSIBILITY-VISCOSITY OF LIGNITE-TYPE ASH'.  A.F. DUZY,1965.
  'RELATIONSHIP OF COAL-ASH VISCOSITY TO CHEMICAL COMPOSTION'.
   W.L. SAGE AND J.B. MCILROY,1960.
** OTL=OUTSIDE TABLE LIMITS. ND=NOT DETERMINED.
```

Rice Hulls

```
ELEMENTAL ANALYSIS OF ASH (%)           ASH FUSION TEMPERATURES (DEG F)
-----------------------------           -------------------------------

      SIO2       96.52                          OXIDIZING        REDUCING
      AL2O3       0.63                          ATMOSPHERE       ATMOSPHERE
      TIO2        0.05
      FE2O3       1.04        INITIAL             ND **           > 2700
      CAO         0.30        SOFTENING
      MGO         0.34        HEMISPHERICAL
      NA2O        0.16        FLUID
      K2O         3.01
      P2O5        0.77
      SO3        <0.01
                 ------
      TOTAL     102.82

ASH VISCOSITY CALCULATIONS *
----------------------------
      BASE CONTENT (%)            4.75
      ACID CONTENT (%)           95.25
      DOLOMITE RATIO             13.20
      BASE/ACID RATIO             0.05
      SILICA/ALUMINA RATIO      153.21
      T(CV),DEG F                ND **
      T250 TEMPERATURE (DEG F)  OTL **
      EQUIV SILICA CONTENT (%)   98.29
      VISCOSITY FROM EQUIV
         SILICA (POISE),2600 F  >999.99
      ASH TYPE                  HIGH RANK
```

% MnO = 0.25

```
* 'FUSIBILITY-VISCOSITY OF LIGNITE-TYPE ASH'.  A.F. DUZY,1965.
  'RELATIONSHIP OF COAL-ASH VISCOSITY TO CHEMICAL COMPOSTION'.
   W.L. SAGE AND J.B. MCILROY,1960.
** OTL=OUTSIDE TABLE LIMITS. ND=NOT DETERMINED.
```

Rice Straw

ELEMENTAL ANALYSIS OF ASH (%)

SIO2	86.08
AL2O3	0.40
TIO2	0.10
FE2O3	0.50
CAO	0.30
MGO	1.73
NA2O	1.58
K2O	11.71
P2O5	1.74
SO3	<0.01
TOTAL	104.14

ASH FUSION TEMPERATURES (DEG F)

	OXIDIZING ATMOSPHERE	REDUCING ATMOSPHERE
INITIAL	ND **	> 2700
SOFTENING		
HEMISPHERICAL		
FLUID		

ASH VISCOSITY CALCULATIONS *

BASE CONTENT (%)	15.45
ACID CONTENT (%)	84.55
DOLOMITE RATIO	12.83
BASE/ACID RATIO	0.18
SILICA/ALUMINA RATIO	215.20
T(CV),DEG F	ND **
T250 TEMPERATURE (DEG F)	OTL **
EQUIV SILICA CONTENT (%)	97.14
VISCOSITY FROM EQUIV SILICA (POISE),2600 F	>999.99
ASH TYPE	LIGNITE

% MnO = 0.69

* 'FUSIBILITY-VISCOSITY OF LIGNITE-TYPE ASH'. A.F. DUZY,1965. 'RELATIONSHIP OF COAL-ASH VISCOSITY TO CHEMICAL COMPOSTION'. W.L. SAGE AND J.B. MCILROY,1960.

** OTL=OUTSIDE TABLE LIMITS. ND=NOT DETERMINED.

Sugar Cane Bagasse

ELEMENTAL ANALYSIS OF ASH (%)

SIO2	15.16
AL2O3	0.40
TIO2	0.06
FE2O3	0.86
CAO	9.16
MGO	5.85
NA2O	1.07
K2O	32.28
P2O5	11.87
SO3	<0.01

TOTAL	76.71

ASH FUSION TEMPERATURES (DEG F)

	OXIDIZING ATMOSPHERE	REDUCING ATMOSPHERE
INITIAL	ND **	2175
SOFTENING		2275
HEMISPHERICAL		2291
FLUID		2300

ASH VISCOSITY CALCULATIONS *

BASE CONTENT (%)	75.91
ACID CONTENT (%)	24.09
DOLOMITE RATIO	30.50
BASE/ACID RATIO	3.15
SILICA/ALUMINA RATIO	37.90
T(CV),DEG F	ND **
T250 TEMPERATURE (DEG F)	OTL **
EQUIV SILICA CONTENT (%)	48.86
VISCOSITY FROM EQUIV SILICA (POISE),2600 F	7.50
ASH TYPE	LIGNITE

% MnO = 0.09

---

* 'FUSIBILITY-VISCOSITY OF LIGNITE-TYPE ASH'. A.F. DUZY,1965. 'RELATIONSHIP OF COAL-ASH VISCOSITY TO CHEMICAL COMPOSTION'. W.L. SAGE AND J.B. MCILROY,1960.

** OTL=OUTSIDE TABLE LIMITS. ND=NOT DETERMINED.

Walnut Shells

ELEMENTAL ANALYSIS OF ASH (%)

SIO2	4.75
AL2O3	0.40
TIO2	0.06
FE2O3	0.50
CAO	22.65
MGO	2.75
NA2O	9.57
K2O	15.08
P2O5	4.55
SO3	<0.01
TOTAL	60.31

ASH FUSION TEMPERATURES (DEG F)

	OXIDIZING ATMOSPHERE	REDUCING ATMOSPHERE
INITIAL	ND **	1401
SOFTENING		1425
HEMISPHERICAL		1440
FLUID		1630

ASH VISCOSITY CALCULATIONS *

BASE CONTENT (%)	90.66
ACID CONTENT (%)	9.34
DOLOMITE RATIO	50.25
BASE/ACID RATIO	9.70
SILICA/ALUMINA RATIO	11.88
T(CV),DEG F	ND **
T250 TEMPERATURE (DEG F)	OTL **
EQUIV SILICA CONTENT (%)	15.50
VISCOSITY FROM EQUIV SILICA (POISE),2600 F	<1.00
ASH TYPE	LIGNITE

% MnO = 0.08

* 'FUSIBILITY-VISCOSITY OF LIGNITE-TYPE ASH'. A.F. DUZY,1965.
'RELATIONSHIP OF COAL-ASH VISCOSITY TO CHEMICAL COMPOSTION'.
W.L. SAGE AND J.B. MCILROY,1960.

** OTL=OUTSIDE TABLE LIMITS. ND=NOT DETERMINED.

Wheat Straw

ELEMENTAL ANALYSIS OF ASH (%)

SIO2	67.88
AL2O3	0.58
TIO2	0.06
FE2O3	0.96
CAO	2.14
MGO	2.53
NA2O	0.56
K2O	17.52
P2O5	6.76
SO3	<0.01
TOTAL	98.99

ASH FUSION TEMPERATURES (DEG F)

	OXIDIZING ATMOSPHERE	REDUCING ATMOSPHERE
INITIAL	ND **	1599
SOFTENING		2345
HEMISPHERICAL		2470
FLUID		2520

ASH VISCOSITY CALCULATIONS *

BASE CONTENT (%)	25.71
ACID CONTENT (%)	74.29
DOLOMITE RATIO	19.70
BASE/ACID RATIO	0.35
SILICA/ALUMINA RATIO	117.03
T(CV),DEG F	ND **
T250 TEMPERATURE (DEG F)	2521
EQUIV SILICA CONTENT (%)	92.34
VISCOSITY FROM EQUIV SILICA (POISE),2600 F	>999.99
ASH TYPE	LIGNITE

% MnO = 0.06

* 'FUSIBILITY-VISCOSITY OF LIGNITE-TYPE ASH'. A.F. DUZY,1965.
'RELATIONSHIP OF COAL-ASH VISCOSITY TO CHEMICAL COMPOSTION'.
W.L. SAGE AND J.B. MCILROY,1960.

** OTL=OUTSIDE TABLE LIMITS. ND=NOT DETERMINED.

Fir Bark

ELEMENTAL ANALYSIS OF ASH (%)

SIO2	5.35
AL2O3	3.35
TIO2	0.10
FE2O3	1.19
CAO	47.76
MGO	5.11
NA2O	1.00
K2O	8.55
P2O5	5.05
SO3	<0.01
TOTAL	77.46

ASH FUSION TEMPERATURES (DEG F)

	OXIDIZING ATMOSPHERE	REDUCING ATMOSPHERE
INITIAL	ND **	2612
SOFTENING		2615
HEMISPHERICAL		2626
FLUID		2676

ASH VISCOSITY CALCULATIONS *

BASE CONTENT (%)	87.85
ACID CONTENT (%)	12.15
DOLOMITE RATIO	83.12
BASE/ACID RATIO	7.23
SILICA/ALUMINA RATIO	1.60
T(CV),DEG F	ND **
T250 TEMPERATURE (DEG F)	OTL **
EQUIV SILICA CONTENT (%)	9.01
VISCOSITY FROM EQUIV SILICA (POISE),2600 F	<1.00
ASH TYPE	LIGNITE

% MnO = 1.66

* 'FUSIBILITY-VISCOSITY OF LIGNITE-TYPE ASH'. A.F. DUZY,1965.
'RELATIONSHIP OF COAL-ASH VISCOSITY TO CHEMICAL COMPOSTION'.
W.L. SAGE AND J.B. MCILROY,1960.

** OTL=OUTSIDE TABLE LIMITS. ND=NOT DETERMINED.

Mixed Hardwood

ELEMENTAL ANALYSIS OF ASH (%)

SIO2	4.75
AL2O3	0.40
TIO2	0.05
FE2O3	0.52
CAO	47.03
MGO	3.35
NA2O	0.78
K2O	7.83
P2O5	4.28
SO3	<0.01

TOTAL	68.99

ASH FUSION TEMPERATURES (DEG F)

	OXIDIZING ATMOSPHERE	REDUCING ATMOSPHERE
INITIAL	ND **	> 2700
SOFTENING		
HEMISPHERICAL		
FLUID		

ASH VISCOSITY CALCULATIONS *

BASE CONTENT (%)	91.96
ACID CONTENT (%)	8.04
DOLOMITE RATIO	84.66
BASE/ACID RATIO	11.44
SILICA/ALUMINA RATIO	11.87
T(CV),DEG F	ND **
T250 TEMPERATURE (DEG F)	OTL **
EQUIV SILICA CONTENT (%)	8.54
VISCOSITY FROM EQUIV SILICA (POISE),2600 F	<1.00
ASH TYPE	LIGNITE

% MnO = 0.53

* 'FUSIBILITY-VISCOSITY OF LIGNITE-TYPE ASH'. A.F. DUZY,1965.
'RELATIONSHIP OF COAL-ASH VISCOSITY TO CHEMICAL COMPOSTION'.
W.L. SAGE AND J.B. MCILROY,1960.

** OTL=OUTSIDE TABLE LIMITS. ND=NOT DETERMINED.

Pine Wee Chips

```
ELEMENTAL ANALYSIS OF ASH (%)           ASH FUSION TEMPERATURES (DEG F)
-----------------------------           -------------------------------

      SIO2         6.24                              OXIDIZING       REDUCING
      AL2O3        0.48                              ATMOSPHERE      ATMOSPHERE
      TIO2         0.06
      FE2O3        1.12           INITIAL              ND **          > 2700
      CAO         24.38           SOFTENING
      MGO          9.15           HEMISPHERICAL
      NA2O         1.04           FLUID
      K2O         22.66
      P2O5        15.61
      SO3         <0.01
                 ------
      TOTAL       80.74

ASH VISCOSITY CALCULATIONS *
----------------------------
      BASE CONTENT (%)           89.59
      ACID CONTENT (%)           10.41
      DOLOMITE RATIO             57.46
      BASE/ACID RATIO             8.61
      SILICA/ALUMINA RATIO       13.00
      T(CV),DEG F                ND **
      T250 TEMPERATURE (DEG F)  OTL **
      EQUIV SILICA CONTENT (%)   15.26
      VISCOSITY FROM EQUIV
         SILICA (POISE),2600 F   <1.00
      ASH TYPE                  LIGNITE
```

% MnO = 1.28

```
* 'FUSIBILITY-VISCOSITY OF LIGNITE-TYPE ASH'.  A.F. DUZY,1965.
  'RELATIONSHIP OF COAL-ASH VISCOSITY TO CHEMICAL COMPOSTION'.
   W.L. SAGE AND J.B. MCILROY,1960.
** OTL=OUTSIDE TABLE LIMITS. ND=NOT DETERMINED.
```

Redwood Bark

ELEMENTAL ANALYSIS OF ASH (%)

SIO2	23.98
AL2O3	10.68
TIO2	0.40
FE2O3	5.75
CAO	18.21
MGO	5.85
NA2O	3.99
K2O	12.69
P2O5	5.06
SO3	<0.01
TOTAL	86.61

ASH FUSION TEMPERATURES (DEG F)

	OXIDIZING ATMOSPHERE	REDUCING ATMOSPHERE
INITIAL	ND **	2233
SOFTENING		2237
HEMISPHERICAL		2239
FLUID		2254

ASH VISCOSITY CALCULATIONS *

BASE CONTENT (%)	57.01
ACID CONTENT (%)	42.99
DOLOMITE RATIO	51.75
BASE/ACID RATIO	1.33
SILICA/ALUMINA RATIO	2.25
T(CV),DEG F	ND **
T250 TEMPERATURE (DEG F)	2094
EQUIV SILICA CONTENT (%)	44.58
VISCOSITY FROM EQUIV SILICA (POISE),2600 F	4.53
ASH TYPE	LIGNITE

% MnO = 0.48

* 'FUSIBILITY-VISCOSITY OF LIGNITE-TYPE ASH'. A.F. DUZY,1965. 'RELATIONSHIP OF COAL-ASH VISCOSITY TO CHEMICAL COMPOSTION'. W.L. SAGE AND J.B. MCILROY,1960.

** OTL=OUTSIDE TABLE LIMITS. ND=NOT DETERMINED.

Redwood Sawdust

ELEMENTAL ANALYSIS OF ASH (%)

SIO2	33.70
AL2O3	6.98
TIO2	0.24
FE2O3	7.87
CAO	26.98
MGO	6.86
NA2O	2.29
K2O	5.76
P2O5	6.66
SO3	<0.01
TOTAL	97.34

ASH FUSION TEMPERATURES (DEG F)

	OXIDIZING ATMOSPHERE	REDUCING ATMOSPHERE
INITIAL	ND **	2318
SOFTENING		2363
HEMISPHERICAL		2369
FLUID		2384

ASH VISCOSITY CALCULATIONS *

BASE CONTENT (%)	54.87
ACID CONTENT (%)	45.13
DOLOMITE RATIO	68.01
BASE/ACID RATIO	1.22
SILICA/ALUMINA RATIO	4.83
T(CV),DEG F	ND **
T250 TEMPERATURE (DEG F)	2279
EQUIV SILICA CONTENT (%)	44.69
VISCOSITY FROM EQUIV SILICA (POISE),2600 F	4.59
ASH TYPE	LIGNITE

% MnO = 0.72

* 'FUSIBILITY-VISCOSITY OF LIGNITE-TYPE ASH'. A.F. DUZY,1965.
'RELATIONSHIP OF COAL-ASH VISCOSITY TO CHEMICAL COMPOSTION'.
W.L. SAGE AND J.B. MCILROY,1960.

** OTL=OUTSIDE TABLE LIMITS. ND=NOT DETERMINED.

South Carolina Tree Chips

ELEMENTAL ANALYSIS OF ASH (%)

SIO2	33.61
AL2O3	2.65
TIO2	0.19
FE2O3	2.20
CAO	40.84
MGO	5.87
NA2O	1.03
K2O	4.98
P2O5	3.42
SO3	<0.01
TOTAL	94.99

ASH FUSION TEMPERATURES (DEG F)

	OXIDIZING ATMOSPHERE	REDUCING ATMOSPHERE
INITIAL	ND **	2510
SOFTENING		2515
HEMISPHERICAL		2520
FLUID		2525

ASH VISCOSITY CALCULATIONS *

BASE CONTENT (%)	59.98
ACID CONTENT (%)	40.02
DOLOMITE RATIO	85.05
BASE/ACID RATIO	1.50
SILICA/ALUMINA RATIO	11.79
T(CV),DEG F	ND **
T250 TEMPERATURE (DEG F)	2520
EQUIV SILICA CONTENT (%)	40.73
VISCOSITY FROM EQUIV SILICA (POISE),2600 F	2.98
ASH TYPE	LIGNITE

% MnO = 2.15

* 'FUSIBILITY-VISCOSITY OF LIGNITE-TYPE ASH'. A.F. DUZY,1965. 'RELATIONSHIP OF COAL-ASH VISCOSITY TO CHEMICAL COMPOSTION'. W.L. SAGE AND J.B. MCILROY,1960.

** OTL=OUTSIDE TABLE LIMITS. ND=NOT DETERMINED.

APPENDIX C

Winegartner and Rhodes Ash Fusion Equations

Combined Eastern and Western Coals

		REDUCING				OXIDIZING				
NO	TERM	ID	H=W	H=W/2	FLUID	ID	H=W	H=W/2	FLUID	
11	EXP[(Si. Val)$^2 \cdot 10^{-1}$]									11
12	% P_2O_5 on Ash			-63.33		-25.299	-20.6887		-40.679	12
13	% SiO_2 on Ash	121.64								13
14	% FeO on Ash									14
15	% Al_2O_3 on Ash		-27.50	-58.14						15
16	% TiO_2 on Ash			-15.85						16
17	% CaO on Ash		6.50			21.065				17
18	% MgO on Ash		-20.20	-26.85		-10.717	-0.1225	-6.3565	-13.175	18
19	% K_2O on Ash		-38.31	-40.17			12.0603			19
20	% Na_2O on Ash		-90.56	-121.87	-62.35	-71.550	-47.7657		-49.479	20
21	% Na_2O on Coal		86.04	354.32	405.20	152.316	69.9142		286.076	21
22	Sq. % P_2O_5 on Ash	71.59						20.20		22
23	Sq. % SiO_2 on Ash	-1.49								23
24	Sq. % FeO on Ash					0.22691	0.34750			24
25	Sq. % Al_2O_3 on Ash		1.65	2.21						25
26	Sq. % TiO_2 on Ash					10.9319	6.36913			26
27	Sq. % CaO on Ash	0.27		0.0581	0.1370		0.30105			27
28	Sq. % MgO on Ash					0.91405				28
29	Sq. % K_2O on Ash							6.835		29
30	Sq. % Na_2O on Ash			1.3126		4.8651	3.47207	2.316	3.14642	30
31	Sq. % Na_2O on Coal			-325.96	-420.63				-307.021	31
32	% SiO_2 · % FeO		-0.14567	-0.3751	-0.1076					32
33	% SiO_2 · % Al_2O_3				0.1240					33
34	% SiO_2 · % CaO	-0.32	-0.36969	-0.3089	-0.1355	-0.31271	-0.36282	-0.2759	-0.50465	34
35	% FeO · % Al_2O_3			0.3916	0.6348					35
36	% FeO · % CaO						0.69220	-0.1578		36
37	% FeO · % MgO							-0.6212	-0.56315	37
38	% Al_2O_3 · % CaO		-0.35790							38
39	% CaO · % MgO		0.30285	0.3913			0.82175			39
40	% SiO_2 + % Al_2O_3									40
41	% CaO + % MgO									41
42	% FeO/% CaO		0.62864			1.0352				42
43	% SiO_2/% Al_2O_3								17.0641	43
44	Sq. (% SiO_2/% Al_2O_3)	6.37				4.0938	2.59128			44
45	% CaO + % MgO/% FeO								5.4059	45
46	% Base	-88.53			-21.45					46
47	Sq. (% Base)	3.62	0.73453		0.9046			1.3816	0.11674	47
48	EXP[10^{-1}((Base/Acid)-1)^2]	-4560		1813.42		1036.45	1167.92	-1570.78	2153.71	48
49	Sq. Dolomite Ratio									49
50	Base/Acid	-7191.94			-1695.21		-387.77	-4362.51		50
51	Sq. (Base/Acid)		-880.85					615.29		51
52	Sq. [(Base/Acid)-1]	1710.78	994.76	-434.16	96.69	-329.564	-277.90		-475.888	52
53	% Na_2O · (Base/Acid)	16.99	62.58	53.85	36.36	37.775	44.286		19.371	53
54	% FeO/Base		-562.40	-1015.41				866.67		54
55	R250	-3030								55
56	Abs. Val. [(Base/Acid)-1]	497.25	278.48	232.03	296.13	226.672	230.725	308.18	289.166	56
57	Silica Value									57
58	Sq. Silica Value									58
59	Dolomite Ratio	847.0		-455.88	238.35		386.64	951.47	413.39	59
61	EXP (10^{-4} · SiO_2 · Al_2O_3)					6999.17	4267.73	2106.16	2372.71	61
62	EXP [10^{-2} · (SiO_2 + Al_2O_3)]									62
	Constant	7482.84	1920.67	2070.87	2449.30	-4054.32	-3440.30	1403.44	-2329.98	
	Standard Error	36.46	47.18	51.66	72.29	67.01	44.60	45.13	40.863	
	R	0.968	0.944	0.9313	0.8494	0.7777	0.925	0.9317	0.9337	
	Original Data $\bar{x}$	2097.38	2161.06	2188.20	2254.95	2780.72	2360.57	2390.05	2437.77	
	σ	144.49	142.04	140.58	136.11	105.84	116.42	123.50	135.49	

Combined Eastern and Western Coals

		FL - ID		OXIDIZING - REDUCING				
NO	TERM	REDUCING	OXIDIZING	ID	H-W	H-W/2	FLUID	
11	EXP[(Si. Val)$^2\cdot10^{-1}$]							11
12	% P_2O_5 on Ash							12
13	% SiO_2 on Ash							13
14	% FeO on Ash	-4.23449						14
15	% Al_2O_3 on Ash				35.80511		10.07641	15
16	% TiO_2 on Ash	-31.48030						16
17	% CaO on Ash					-10.792		17
18	% MgO on Ash				4.07820			18
19	% K_2O on Ash			31.59633	37.32117	47.429		19
20	% Na_2O on Ash		29.99590	-16.40253		23.561		20
21	% Na_2O on Coal							21
22	Sq. % P_2O_5 on Ash							22
23	Sq. % SiO_2 on Ash							23
24	Sq. % FeO on Ash		-0.05271	0.07012	0.08668		0.03453	24
25	Sq. % Al_2O_3 on Ash				-1.28085	-0.32676		25
26	Sq. % TiO_2 on Ash		-16.47279					26
27	Sq. % CaO on Ash							27
28	Sq. % MgO on Ash			0.33114				28
29	Sq. % K_2O on Ash							29
30	Sq. % Na_2O on Ash		-2.37050	4.44273	3.76980	3.23637	3.88566	30
31	Sq. % Na_2O on Coal							31
32	% SiO_2 · % FeO		0.24730		0.15143	0.13508	0.53294	32
33	% SiO_2 · % Al_2O_3							33
34	% SiO_2 · % CaO	-0.09872	-0.18819	0.07567				34
35	% FeO · % Al_2O_3		-0.31991		-0.26558	-0.26048	-0.39985	35
36	% FeO · % CaO							36
37	% FeO · % MgO			-0.52814	-0.31546	-0.51051		37
38	% Al_2O_3 · % CaO			0.18812		0.26411		38
39	% CaO · % MgO		-0.24090					39
40	% SiO_2 + % Al_2O_3							40
41	% CaO + % MgO							41
42	% FeO/% CaO		-2.15705		-0.91030	-1.04581	-1.30657	42
43	% SiO_2/% Al_2O_3							43
44	Sq. (% SiO_2/% Al_2O_3)					-1.62419		44
45	% CaO + % MgO/% FeO			-3.84078			5.88890	45
46	% Base							46
47	Sq. (% Base)							47
48	EXP[10^{-1}((Base/Acid)-1)^2]							48
49	Sq. Dolomite Ratio	-203.44	317.66		263.37	319.03		49
50	Base/Acid							50
51	Sq. (Base/Acid)				11.32	80.55	20.70	51
52	Sq. [(Base/Acid)-1]					-88.45433		52
53	% Na_2O · (Base/Acid)				-10.35142	-22.55943	-16.36078	53
54	% FeO/Base			546.47754	615.48877	1043.58276	-198.82159	54
55	R250							55
56	Abs. Val. [(Base/Acid)-1]		37.39067					56
57	Silica Value							57
58	Sq. Silica Value							58
59	Dolomite Ratio					485.22803		59
61	EXP (10^{-4} · SiO_2 ·Al_2O_3)							61
62	EXP [10^{-2} · (SiO_2 + Al_2O_3)]							62
	Constant	383.034	71.9357	-137.122	-505.615	-487.586	-188.44122	
	Standard Error	77.576	72.7436	59.1657	46.971	49.7095	64.3762	

		REDUCING				OXIDIZING				
NO	TERM	ID	H-W	H-W/2	FLUID	ID	H-W	H-W/2	FLUID	
11	EXP[(Si. Val)$^2 \cdot 10^{-1}$]				18004.56	4064.41				11
12	% P_2O_5 on Ash									12
13	% SiO_2 on Ash									13
14	% FeO on Ash		18.2291							14
15	% Al_2O_3 on Ash				59.7401					15
16	% TiO_2 on Ash									16
17	% CaO on Ash									17
18	% MgO on Ash					-43.35294		-28.12042		18
19	% K_2O on Ash	-45.9983				22.33795				19
20	% Na_2O on Ash	-116.8924	-15.1153	-114.364		-45.56789	-65.74098	-31.76306	-30.71465	20
21	% Na_2O on Coal		451.0349	427.915	574.534	203.48790		106.75958	289.55981	21
22	Sq. % P_2O_5 on Ash									22
23	Sq. % SiO_2 on Ash									23
24	Sq. % FeO on Ash	0.1373		0.26855	0.18512	0.14325			0.02612	24
25	Sq. % Al_2O_3 on Ash					0.58453				25
26	Sq. % TiO_2 on Ash	49.0649				60.14096		33.89645		26
27	Sq. % CaO on Ash		0.4566	0.65427	0.57118					27
28	Sq. % MgO on Ash					4.92741			-3.53403	28
29	Sq. % K_2O on Ash			-9.23755						29
30	Sq. % Na_2O on Ash				-6.99908					30
31	Sq. % Na_2O on Coal	86.3835	-538.4807	-394.2317	-508.0742		73.15411		-310.11719	31
32	% SiO_2 · % FeO		-0.3269							32
33	% SiO_2 · % Al_2O_3									33
34	% SiO_2 · % CaO	0.1586					-0.35400	-0.62404	-0.48671	34
35	% FeO · % Al_2O_3							-0.39592		35
36	% FeO · % CaO							0.21847	0.19498	36
37	% FeO · % MgO						-1.06789			37
38	% Al_2O_3 · % CaO									38
39	% CaO · % MgO							-1.01475		39
40	% SiO_2 + % Al_2O_3									40
41	% CaO + % MgO									41
42	% FeO/% CaO	0.6213								42
43	% SiO_2/% Al_2O_3						-26.48494	-32.02823		43
44	Sq. (% SiO_2/% Al_2O_3)	4.3156								44
45	% CaO + % MgO/% FeO			-41.8782					34.98683	45
46	% Base									46
47	Sq. (% Base)		2.4871					0.05274		47
48	EXP[10^{-1}((Base/Acid)-1)^2]									48
49	Sq. Dolomite Ratio							659.55		49
50	Base/Acid		-7618.8281							50
51	Sq. (Base/Acid)		611.3500	-201.12			83.0000			51
52	Sq. [(Base/Acid)-1]	-578.4041								52
53	% Na_2O · (Base/Acid)	102.8146		98.5841			36.11714			53
54	% FeO/Base	-1920.5200		-1899.18			-546.81055		-228.72809	54
55	R250									55
56	Abs. Val. [(Base/Acid)-1]	319.8220	653.7610	200.763		-162.68340				56
57	Silica Value									57
58	Sq. Silica Value									58
59	Dolomite Ratio	-1767.8857		-1588.58			-448.22510			59
61	EXP ($10^{-4} \cdot SiO_2 \cdot Al_2O_3$)	6019.2	2685.1900	4002.36	-8569.39					61
62	EXP [$10^{-2} \cdot (SiO_2 + Al_2O_3)$]									62
	Constant	-2845.38	-351.30	-698.51	-8356.8	-2014.25	3199.72	2827.81	2800.81	
	Standard Error	44.3172	44.4052	52.9720	84.51	76.516	45.522	46.149	48.788	
	R	0.871	0.908	0.8840	0.763	0.675	0.852	0.840	0.767	
	Original Data $\bar{x}$	1996.56	2078.42	2115.54	2220.79	2291.46	2410.26	2452.14	2521.38	
	σ	89.15	104.93	112.12	130.05	102.86	86.38	84.25	75.45	

Eastern Coals Only

Eastern Coals Only

		FL - ID		OXIDIZING - REDUCING				
NO	TERM	REDUCING	OXIDIZING	ID	H=W	H=W/2	FLUID	
11	EXP[(Si. Val)$^2 \cdot 10^{-1}$]							11
12	% P_2O_5 on Ash							12
13	% SiO_2 on Ash							13
14	% FeO on Ash							14
15	% Al_2O_3 on Ash							15
16	% TiO_2 on Ash							16
17	% CaO on Ash							17
18	% MgO on Ash		74.39572					18
19	% K_2O on Ash			32.63083	21.54579			19
20	% Na_2O on Ash		16.73648					20
21	% Na_2O on Coal				-82.15767	-138.51	-77.01291	21
22	Sq. % P_2O_5 on Ash							22
23	Sq. % SiO_2 on Ash	0.06137		0.09824				23
24	Sq. % FeO on Ash							24
25	Sq. % Al_2O_3 on Ash					-0.5926		25
26	Sq. % TiO_2 on Ash							26
27	Sq. % CaO on Ash	0.30185			-0.21682			27
28	Sq. % MgO on Ash		-10.39283					28
29	Sq. % K_2O on Ash		-4.52715					29
30	Sq. % Na_2O on Ash						2.52436	30
31	Sq. % Na_2O on Coal							31
32	% SiO_2 · % FeO					0.4316	0.31452	32
33	% SiO_2 · % Al_2O_3							33
34	% SiO_2 · % CaO							34
35	% FeO · % Al_2O_3			0.55062	-0.35687			35
36	% FeO · % CaO					0.5048		36
37	% FeO · % MgO							37
38	% Al_2O_3 · % CaO			0.39003				38
39	% CaO · % MgO							39
40	% SiO_2 + % Al_2O_3					-19.15		40
41	% CaO + % MgO					-11.14		41
42	% FeO/% CaO		-2.42994				-1.42293	42
43	% SiO_2/% Al_2O_3		197.18266					43
44	Sq. (% SiO_2/% Al_2O_3)		-19.44696		-6.50774	-4.678		44
45	% CaO + % MgO/% FeO				93.67690	75.05		45
46	% Base							46
47	Sq. (% Base)							47
48	EXP[10^{-1}((Base/Acid)-1)^2]							48
49	Sq. Dolomite Ratio		717.63		445.78			49
50	Base/Acid							50
51	Sq. (Base/Acid)						41.25	51
52	Sq. [(Base/Acid)-1]				194.91562	247.80		52
53	% Na_2O · (Base/Acid)							53
54	% FeO/Base			336.96216	719.71411			54
55	R250			-751.65		2040.79		55
56	Abs. Val. [(Base/Acid)-1]							56
57	Silica Value							57
58	Sq. Silica Value							58
59	Dolomite Ratio	-317.8375	-774.7653					59
61	EXP (10^{-4} · SiO_2 ·Al_2O_3)				-4806.56			61
62	EXP [10^{-2} · (SiO_2 + Al_2O_3)]							62
	Constant	105.40	-205.17117	109.378	5185.695	-157.84	-30.349	
	Standard Error	93.976	86.247	67.651	51.974	56.627	76.716	

NO	TERM	REDUCING				OXIDIZING				
		ID	H-W	H-W/2	FLUID	ID	H-W	H-W/2	FLUID	
11	EXP[(Si. Val)$^2 \cdot 10^{-1}$]									11
12	% P_2O_5 on Ash		-206.326			-83.6118		-37.1017		12
13	% SiO_2 on Ash								102.933	13
14	% FeO on Ash									14
15	% Al_2O_3 on Ash	-32.3515		-33.2618	-32.8180	-42.9729			65.619	15
16	% TiO_2 on Ash								67.530	16
17	% CaO on Ash	5.66115								17
18	% MgO on Ash			-7.38767					-18.3378	18
19	% K_2O on Ash									19
20	% Na_2O on Ash	-40.5915		-27.9290	-20.5327					20
21	% Na_2O on Coal					-625.926				21
22	Sq. % P_2O_5 on Ash	29.8772				26.6343				22
23	Sq. % SiO_2 on Ash		-1.88451							23
24	Sq. % FeO on Ash									24
25	Sq. % Al_2O_3 on Ash	1.7680	-5.95181	1.90887	1.74939	2.06372			1.42195	25
26	Sq. % TiO_2 on Ash		-87.9517	11.2718						26
27	Sq. % CaO on Ash				0.13041	0.12681	0.03921	0.04192	-0.08562	27
28	Sq. % MgO on Ash									28
29	Sq. % K_2O on Ash					-69.6295				29
30	Sq. % Na_2O on Ash			-0.96708	-1.66777		2.58837	2.53592	1.73981	30
31	Sq. % Na_2O on Coal		2044.68			924.846		321.793		31
32	% SiO_2 · % FeO					-0.46074				32
33	% SiO_2 · % Al_2O_3									33
34	% SiO_2 · % CaO				-0.08915	-0.21820			-0.19302	34
35	% FeO · % Al_2O_3						0.76618	0.86563		35
36	% FeO · % CaO	-0.33316		-0.33403			-0.35566	-0.38046	-0.58439	36
37	% FeO · % MgO									37
38	% Al_2O_3 · % CaO									38
39	% CaO · % MgO									39
40	% SiO_2 + % Al_2O_3									40
41	% CaO + % MgO									41
42	% FeO/% CaO					79.3965				42
43	% SiO_2/% Al_2O_3		181.002					44.7255		43
44	Sq. (% SiO_2/% Al_2O_3)						4.45522			44
45	% CaO + % MgO/% FeO	4.22410	7.49107							45
46	% Base		-645.295				-50.8354	-98.7154		46
47	Sq. (% Base)	1.44721	4.03205	0.34649	0.20239		1.08744	0.86573		47
48	EXP[10^{-1}((Base/Acid)-1)^2]	-2507.79	3782.09	2655.70	2315.31	1605.71	545.39	2179.39	5110.77	48
49	Sq. Dolomite Ratio					-365.49				49
50	Base/Acid	-5058.35					-1381.09			50
51	Sq. (Base/Acid)	784.48							1166.12	51
52	Sq. [(Base/Acid)-1]		-811.879	-480.010	-534.781	-375.460		-482.218	-2472.186	52
53	% Na_2O · (Base/Acid)	34.5307	15.5137	29.3304	37.4419	10.5107				53
54	% FeO/Base	255.309								54
55	R250									55
56	Abs. Val. [(Base/Acid)-1]	362.099	239.499	232.863	280.888	271.058	285.470	256.667	214.003	56
57	Silica Value									57
58	Sq. Silica Value		-12552.4				-1598.82	-2964.9	-2782.34	58
59	Dolomite Ratio									59
61	EXP (10^{-4} · SiO_2 ·Al_2O_3)						5547.56	4071.1		61
62	EXP [10^{-2} · (SiO_2 + Al_2O_3)]			1389.60	1230.04					62
	Constant	5274.95	25804.8	-2745.07	-2533.72	1354.48	-2681.4	-1041.69	-7741.18	
	Standard Error	46.648	30.064	41.897	51.507	46.550	37.184	37.75	42.81	
	R	0.909	0.970	0.944	0.924	0.905	0.953	0.956	0.944	
	Original Data $\bar{x}$	2205.1	2249.4	2265.8	2291.4	2269.3	2307.4	2323.7	2348.5	
	σ	110.6	122.0	125.7	133.0	107.8	120.9	124.3	128.3	

Western Coals Only

Western Coals Only

		FL - ID		OXIDIZING - REDUCING				DATA BASE		
NO	TERM	REDUCING	OXIDIZING	ID	H=W	H=W/2	FLUID	MEAN	STANDARD DEVIATION	
11	EXP[(Si. Val)$^2 \cdot 10^{-1}$]							1.02631	0.01646	11
12	% P_2O_5 on Ash					-12.09054		0.46698	0.36506	12
13	% SiO_2 on Ash							41.29742	11.13863	13
14	% FeO on Ash			-4.1655				6.20856	3.27015	14
15	% Al_2O_3 on Ash				23.4008			11.64719	2.62813	15
16	% TiO_2 on Ash							0.93412	0.33352	16
17	% CaO on Ash							28.49852	9.60496	17
18	% MgO on Ash							9.03446	3.22671	18
19	% K_2O on Ash	40.9[illegible]3	74.9024					0.31863	0.26382	19
20	% Na_2O on Ash				10.2088			1.58996	1.37885	20
21	% Na_2O on Coal							0.12482	0.08325	21
22	Sq. % P_2O_5 on Ash							0.35113	0.62459	22
23	Sq. % SiO_2 on Ash	0.02016						1829.43164	1029.11768	23
24	Sq. % FeO on Ash		0.41298					49.22247	77.90744	24
25	Sq. % Al_2O_3 on Ash		-0.49375		-0.81243			142.56323	65.98618	25
26	Sq. % TiO_2 on Ash							0.98368	0.74221	26
27	Sq. % CaO on Ash	0.04794						904.32300	498.93970	27
28	Sq. % MgO on Ash							92.02324	60.31854	28
29	Sq. % K_2O on Ash			-23.6180				0.17101	0.31573	29
30	Sq. % Na_2O on Ash	-0.42449		3.96643	3.37480	3.59628	3.72179	4.42620	12.04152	30
31	Sq. % Na_2O on Coal			350.1426				0.02250	0.03939	31
32	% SiO_2 · % FeO		-0.24299		0.18990	-.45451	0.56519	247.35378	121.73523	32
33	% SiO_2 · % Al_2O_3							498.95505	234.55702	33
34	% SiO_2 · % CaO	-0.06212	-0.13597			-0.08560	-0.08783	1076.76342	236.35361	34
35	% FeO · % Al_2O_3			0.63711				71.55591	38.90419	35
36	% FeO · % CaO		-0.54078		-0.08425			176.81569	101.69472	36
37	% FeO · % MgO							55.92323	25.68282	37
38	% Al_2O_3 · % CaO		0.29088					313.93894	90.73698	38
39	% CaO · % MgO							282.95239	158.56311	39
40	% SiO_2 + % Al_2O_3							52.94513	12.91866	40
41	% CaO + % MgO							37.53322	12.39758	41
42	% FeO/% CaO	-120.3456	-364.69604			58.52953	86.01013	0.27015	0.24365	42
43	% SiO_2/% Al_2O_3					-9.27048	-11.76445	3.60217	0.84380	43
44	Sq. (% SiO_2/% Al_2O_3)							13.68620	6.96293	44
45	% CaO + % MgO/% FeO			-3.89388				7.00741	3.20348	45
46	% Base							43.65047	12.92058	46
47	Sq. (% Base)							2250.66040	1075.36128	47
48	EXP[10^{-1}((Base/Acid)-1)^2]						217.54	1.02329	0.06328	48
49	Sq. Dolomite Ratio	-360.24						0.65958	0.13657	49
50	Base/Acid							0.95213	0.66625	50
51	Sq. (Base/Acid)			18.97	24.03			1.12185	1.16345	51
52	Sq. [(Base/Acid)-1]					20.02452		0.21755	0.46365	52
53	% Na_2O · (Base/Acid)			-21.3742	-22.9069	-17.58565	-19.69362	1.67530	1.82187	53
54	% FeO/Base		1515.156			-870.892	-1070.009	0.14710	0.07933	54
55	B250							0.60002	0.12670	55
56	Abs. Val. [(Base/Acid)-1]							0.34982	0.30877	56
57	Silica Value							0.48839	0.14206	57
58	Sq. Silica Value							0.25868	0.15837	58
59	Dolomite Ratio							0.80680	0.09270	59
61	EXP (10^{-4} · SiO_2 · Al_2O_3)							1.05143	0.02505	61
62	EXP [10^{-2} · (SiO_2 + Al_2O_3)]							1.71771	0.23392	62
	Constant	331.95	204.41	54.784	-150.50	189.34	-12.63			
	Standard Error	51.367	48.948	42.163	34.454	35.895	45.653			
	R	0.666	0.691	0.738	0.751	0.747	0.676			
	Original Data $\bar{y}$	86.34	79.70	64.16	58.06	57.91	57.02			
	σ	68.25	61.19	62.09	51.79	58.61	61.35			