**BIOMASS FUEL CHARACTERIZATION:
TESTING AND EVALUATING THE COMBUSTION CHARACTERISTICS
OF SELECTED BIOMASS FUELS**

Final Report

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by

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BIOMASS FUEL CHARACTERIZATION: TESTING AND EVALUATING THE COMBUSTION CHARACTERISTICS OF SELECTED BIOMASS FUELS

1.0 INTRODUCTION

It is general knowledge that man has been using wood and other forms of flammable organic material to produce heat energy since before recorded history. Despite the length of time that man has had to study the physical and chemical nature of these organic fuels, there are considerable gaps in the pure and applied science of solid biomass¹ fuel combustion.

One reason for the lack of biomass combustion knowledge is the complexity of solid fuel combustion reactions in general. Another reason for the lack of knowledge, is that by the time engineers and scientists became adept enough to study the complex phenomena of solid combustion in general, the primary fuels of interest were coal, gas, and oil (fossil fuels), not wood or municipal solid waste. This has begun to change since the advent of the idea that nonrenewable energy sources such as coal, oil, and nuclear fission, are not necessarily the best ways to deal with future global energy needs. It has become apparent that large, centralized, power producing facilities may not be as efficient at meeting consumer demands as smaller more regionally designed power systems. This may be particularly true in certain cases where inexpensive biomass fuel is available in large quantities. It is also true that these same communities or regions are having difficulty

¹For this report "biomass" is defined as any organic (carbon based) fuel; including wood, agricultural residue, Municipal Solid Waste (MSW), and Refuse Derived Fuel ("derived" from MSW by mechanical means such as screens and air classifiers). It does not include fossil fuels such as coal, oil, and natural gas. The properties of coal are used many times in comparisons with biomass in this report because coal is one of the most thoroughly understood solid fuels at present.

disposing of their combustible waste streams, such as woody biomass or MSW. This situation produces a consummate match of raw material to energy demand. This match is not perfect, woody biomass and MSW fuels contain pitfalls such as the possibility of producing acid-rain, reduced air quality in general, and aiding the chemical degradation of our atmosphere due to heat, carbon dioxide, and carbon monoxide emissions.

The lack of fuel quality characterization (and verifiable specifications) for biomass fuels is believed to be one factor inhibiting their wider commercial acceptance. The valuable nature of biomass fuels presents a range of potential problems for commercial and industrial users, i.e., their energy value, combustion characteristics, fuel feed and handling requirements, and environmental considerations.

Disposal or use of clean and/or contaminated biomass materials is an increasing concern from both a landfill perspective and potential energy use application. There is increasing pressure to resolve the disposal issue through the energy conversion option.

The current practice of landfilling as a method of dealing with the 6.6 million tons of MSW that the Pacific Northwest and Alaska produces each year [1], is fast becoming obsolete due to the scarcity of available land. As the available area for landfilling dwindles, the cost of landfilling becomes more prohibitive. This cost is passed on to the industrial and individual consumers in the form of higher tipping fees.

An alternative to landfilling is to reclaim the energy that is contained with the waste and also reduce its volume. The heat that is produced can be used to produce steam for heating or for electrical generation. Large-scale waste to energy power plants that are operating successfully legitimize the use of municipal and industrial solid wastes as a significant source of energy.

There are several forms in which wood waste and MSW is used as fuel. Raw unprocessed rubbish/trash, etc. is known as municipal solid waste. When the raw waste, or MSW, is processed to remove the noncombustibles the end product becomes known as refuse derived fuel (RDF). It is important to note that there are varying degrees to which the RDF can be processed. Currently, raw MSW, RDF pellets, RDF cubes, RDF fluff and pelletized and natural wood wastes are being studied for possible use as a fuel source.

Unprocessed municipal solid waste is currently the most available fuel form. One advantage of the use of unprocessed MSW fuel is that there is no front-end sorting of material prior to combustion. A drawback of MSW is that there are a lot of non-combustibles (glass, metal, rocks, etc.) which limit the type of burning system that can be used. Refuse derived fuels (RDF) have been processed in varying degrees to remove the noncombustibles from the fuel stream. RDF, providing proper emission control equipment is in place, can be used in existing burning systems with little or no retrofit to accommodate the RDF in place of other solid fuels such as wood or coal. The primary disadvantage of RDF is that it requires front-end processing equipment which is often extremely noisy, dirty, and unreliable.

It is anticipated that the following material will be a useful assemblage of prior knowledge combined with new results to provide a step forward in biomass fuels research.

2.0 SAMPLING PROCEDURES

Data obtained from wood biomass or MSW samples can be used in establishing price, designing feed and combustion systems, determining life cycle costs, determining plant or component efficiency, and for general consumer information.

2.1 Woody Biomass

Wood Biomass is one of the most difficult materials to sample, because of variability attributable to species, environmental factors, handling, processing and desired end-use. Trees of the same species that grow in different environments can have markedly different fuel qualities. The proper collection of a sample requires an understanding and consideration of the physical character, statistical nature, and over-all precision required. This task is further complicated by the sampling equipment available and the quantity to be represented by the sample. Obtaining a sample of reasonable weight to represent a source or "lot" presents difficulties. These difficulties emphasize the necessity for using standard sampling procedures.

This characterization and combustion study required sampling of different species with various levels of contamination. The samples were collected over the five state Northwest region which includes Oregon, Washington, Idaho, Montana and Alaska. Two different methods of collection were used. If the samples came from large abandoned fuel piles they were obtained by filling five 5-gallon buckets from five randomly selected sites on the fuel pile. The samples were taken both from the surface and from within the pile. The samples were stored in an airtight container until time of either pelletizing or further testing. If the samples came from a facility that was operational and currently using the wood biomass as a fuel, samples were taken from a moving conveyor belt or auger system. The five 5-gallon buckets were

filled at five random times as the material moved on the conveying system.

2.2 Municipal Solid Waste

MSW is easier to sample than woody biomass in that it is located at one site. A method used and proposed for further sampling is described. As with wood biomass, five 5-gallon buckets with airtight sealing lids were used for sample collection. A rope 36 feet long with a knot every 4 feet was laid across the refuse material (see Figure 1). A 2-pound (approximately) sample of MSW was obtained from beneath each of the eight knots on the rope. The material was deposited in the buckets and the air tight seals were put into place and remained in place until further testing was performed.

No nationally recognized standard exists for sampling wood biomass or for municipal solid waste. Randomness is important to obtain information that will be statistically relevant.

Figure 1. Diagram of the Sampling Rope Laid Out on the Waste.

3.0 PHYSICAL AND CHEMICAL PROPERTIES OF BIOMASS FUELS

Representative samples of clean and contaminated diversified biomass fuels were obtained from different sites. Hugged fuel was also obtained with portions of it being pelletized. The samples were prepared for laboratory and combustion testing.

3.1 Wood Biomass

3.1.1 Ultimate Analysis

The ultimate analysis of a fuel is a record of the percent by weight of hydrogen (H_2), carbon (C), nitrogen (N_2), oxygen (O_2), sulfur (S), ash (mineral), and sometimes, chlorine (Cl). Currently, *ASTM Standard No. D 3176-84*, "Ultimate Analysis of Coal and Coke," is the procedure used for laboratory samples of wood and refuse derived fuel (RDF) biomass fuels. It is usually given on a moisture free basis. The primary importance of the ultimate analysis is in the calculation of the stoichiometric air-to-fuel (A/F) ratio [2]. Another important aspect is that sulfur and chlorine can be a major cause of emission problems. Sulfur and chlorine are a culprit in boiler flue corrosion due to the acidic nature of their compounds (primarily hydrochloric and sulfuric acids). Sulfur content of most wood based fuels is so low that sulfur dioxide and other pollutants are not a problem [3]. Chlorine, like sulfur, is also a very small component of wood biomass (except for saltwater soaked logs); however, chlorine can play a considerable role in the corrosive behavior of refuse derived fuels [4].

Table 1, compiled from the literature, lists the ultimate analysis of a number of different fuels for comparative purposes. From the table it is possible to denote some general trends in the three fuel categories represented. Those categories being coal, wood, and RDF biomass. First, coal has a low oxygen and high carbon content compared with wood and RDF. Second, coal and RDF have high ash and sulfur

Table 1. Ultimate Analysis Data for Selected Dry Fuels.
Sources [5,6,7,8].

Fuel Type	% by wt.						
	C	H ₂	O ₂	S	N ₂	Cl	Ash
KY, No. 9 coal	65.2	4.6	8.4	.4.9	1.4	—	15.4
WV, Rank D, coal	84.7	4.3	2.2	.6	1.5	—	4.0
Douglas Fir	52.3	6.3	40.5	≈0	.1	—	.8
White Pine	52.5	6.1	41.3	≈0	≈0	—	.1
Black Oak	48.8	6.1	45.0	≈0	≈0	—	.1
RDF, Type A	46.0	6.0	34.5	.4	.7	.4	12.0
RDF, Type D	44.0	6.0	32.6	.3	.7	.4	16.0

content compared to wood. Finally, it is apparent that only RDF has an appreciable amount of chlorine, the exception being for woody biomass that comes from salt soaked logs as seen in Table 2.

For this study nine pellet fuels were tested for their "Chemical Variables".² A compilation of the ultimate analysis data including the minimum (MIN), maximum (MAX), mean, and standard deviation (SDEV) for the nine fuels is shown in Table 2.

It is evident from Table 2, that the elemental composition for these pellet fuels is not too different. The main differences are in chlorine and sulfur, but these are at very small percentages relative to the other constituents. As stated earlier, chlorine, even in small percentages, can be very corrosive to combustion systems, and increases stack gas opacity and particulate loading.

²For a listing of pellet fuel samples refer to Appendixes A and B.

Table 2. Ultimate Analyses for Pellets Coded (1-9).

	C (%)	H ₂ (%)	N ₂ (%)	S (%)	O ₂ (%)	Cl (%)
MIN	50.35	5.82	.10	.01	37.11	.00
MAX	54.16	6.35	.37	.30	42.54	.41
MEAN	51.77	6.09	.21	.05	40.41	.28
SDEV	2.53	.17	.10	.08	1.75	.33

Note: All data are on a (dry-basis)

3.1.2 Proximate Analysis

The proximate analysis of solid fuel is used to determine the percentages of volatile material, fixed carbon, and ash. Volatile matter is the portion of fuel gasified by pyrolytic action and responsible for flaming combustion. Fixed carbon is that portion of fuel, not pyrolyzed, that burns in solid form (glowing or char combustion).

Proximate analyses are done under rigid test conditions as prescribed by *ASTM Standard No.D 3172-73*, "Proximate Analysis of Coal and Coke." The ASTM standard calls for heating the sample at 1740°F for seven minutes. During this heating period the volatiles are driven off.

The fundamental importance of proximate analysis is in the design of combustion systems, especially grates and air handling equipment, for two primary reasons: First, fixed carbon burns at a much slower rate than volatiles and at a higher temperature [9,10]. This is very useful information for grate or fuel bed designers who must choose materials properly for their expected temperature loading. Second, it is important to determine the correct amount of underfire and overfire air for efficient combustion. The underfire air is used to burn the fixed carbon and the overfire air is used to burn the volatiles.

Engineers must also design fire-boxes, ducts, fans, and pollution abatement devices for the total volume of exhaust gases. Matter in the solid state takes up much less volume than matter in the gaseous state. In addition, the volume of gases from the combustion of low volatile fuel will be considerably less than for highly volatile fuels. This is one contributing factor to the problems encountered in cofiring coal with wood or RDF in a boiler designed originally for coal. Wood and RDF have a much higher yield of gases for the same heat output required by the boiler. This usually leads to a loss of efficiency and erosion problems due to high gas velocities. The high velocities are also coupled with increased particulate loading [11].

For many years proximate analyses have been used successfully to determine the ratio of overfire versus underfire air for proper combustion. This is done simply on the basis of knowing the percentage of fixed carbon to volatiles in the fuel. Once a total quantity of deliverable air is chosen, it is split into two air streams, underfire and overfire, in the same ratio respectively as volatile to fixed carbon. This works very well in coal combustion where the percent volatiles is usually low, however, there is some doubt now as to the applicability of this method for higher volatile fuels such as wood and RDF.

Table 3 lists some proximate analyses data for selected biomass and fossil fuels.

The table shows the considerable differences between RDF, coal, and wood, when it comes to proximate analysis. The coal is much higher than wood or RDF in fixed carbon, but is similar in ash to RDF. The two species of wood shown, illustrate how variable the ratio of fixed carbon to volatile matter and ash content can be in different species of wood.

Table 4, shows the statistics for the proximate analysis of the nine wood pellet fuels tested in this study.

Table 3. Proximate Analyses of Selected Dry Biomass Fuels.
Sources [9,12,13].

Fuel Type	% by wt.		
	Fixed Carbon	Volatile Matter	Ash
RDF Type A	13.0	75.0	12.0
RDF Type D	13.0	71.0	16.0
KY, No. 9 Coal	46.1	38.5	15.4
Cedar (Wood)	21.0	77.0	2.0
Douglas Fir (Wood)	13.7	86.2	.1

Table 4. Proximate Analyses for Pellet Fuels (1-9).

	% Volatile	% Fixed Carbon	% Ash
MIN	71.60	15.66	.21
MAX	84.13	25.85	2.74
MEAN	77.56	21.03	1.41
SDEV	4.20	3.29	.94

Note: All data are on a (dry-basis)

3.1.3 Higher Heating Value (HHV)

Higher heating value is primarily used as the basis for energy balance and/or efficiency calculations for boilers, furnaces, and multiple fuel comparisons. The HHV is the quantity of heat released during complete (constant volume) combustion of a fuel. The products of combustion are brought to the same temperature as the initial constituents [2,5,14]. This represents the maximum available combustion energy output that can be expected.

HHV is found by laboratory testing, usually in an adiabatic bomb calorimeter. The applicable ASTM Standard is No. D 2015-77, "Gross Calorific Value of a Solid by the Adiabatic Bomb Calorimeter," and is generally performed on an oven-dry³ sample. It is assumed that the water formed by combustion of hydrogen is in the liquid phase at final equilibrium, this implies that the heat of vaporization of water is included in the higher heating value.

There have been a number of other heating values reported such as: 1) net or lower heating value (LHV) [3,5,7,10,15,16], and 2) lower heating value two (LHV2) [10,15]. These are defined primarily to account for the energy losses due to the water vapor formed during combustion and carried as moisture in the fuel. Note that, higher heating value (HHV) is based on all water formed being in the liquid state.

For LHV, the cited references generally agree that lower heating value is calculated by subtracting the latent heat of vaporization (h_{fg}) from the higher heating value. The value for h_{fg} is 1055 Btu/lbm at 68°F [2].

Lower heating value two (LHV2) is a sophisticated modification to the HHV and accounts for the fact that some of the water in wood or any solid fuel is "bound" by molecular forces that require more energy to break, i.e. vaporize, than if the water were "free". This idea is presented in detail in a later section titled, "Moisture Content."

Table 5 lists higher heating values for a number of wood, coal, and RDF fuels. The examples were chosen to represent the range of HHV's for these fuel types.

³Oven-dry refers to woody biomass that has zero percent moisture content.

Table 5. Higher Heating Value of Selected Biomass Fuels.
Sources [5,6,7,8].

Fuel Type	HHV (dry-basis) (Btu/lbm)
WV, Rank D Coal	14730
ND, Rank J Coal	7210
RDF, Type A	8100
RDF, Type D	7700
RDF, Type 3	9796
Sitka Spruce (Wood)	8100
Ponderosa Pine (Wood)	9100 - 9140
Ponderosa Pine (Bark)	9415 - 9616
Douglas Fir (Wood)	8318 - 9200
Douglas Fir (Bark)	9373 - 10845
Western H	8626

Table 5 shows that the average (wood-only) HHV is 8747 (Btu/lbm), for RDF the average is 8532 (Btu/lbm), and for coal it is 10970 (Btu/lbm). The table illustrates how close RDF and wood biomass can be in higher heating value and how coals HHV is larger than either RDF or wood by approximately 20 percent. Remember, these values are only representative and by no means are the comparisons made definitive.

Table 8 contains HHV information for the pellet fuels tested.

3.1.4 Moisture Content

Moisture content (MC) of a solid fuel is one of the most critical parameters affecting combustion [10]. It affects the rate of burning, flaming temperature, and volume of gases produced during combustion.

Consequently, the moisture content alters boiler performance and emission rates. It has been noted by several authors that combustion of hogged wood fuel in typical boilers will cease or "black-out"⁴ at approximately 67 percent moisture content wet-basis [17,18,19]. Black-out usually necessitates the use of additional fossil fuel to maintain combustion such as oil or natural gas. Moisture also lowers the heat or Btu content per pound of fuel, which means a greater volume and mass must be fired to achieve the same steam or heat load as compared to dry fuel. The following section describes the typical calculations to account for heat losses due to moisture content and some of the current work being done to study the effect of moisture on combustion. The applicable ASTM Standard is, No. E 871-82, "Moisture Analysis of Particulate Wood Fuels."

Moisture in fuel is described by one of two equivalent ways, either on a "wet" or "dry" percentage basis. Wet Basis (wb) is defined as the weight of water in the sample (water weight), divided by the total sample weight (sample weight) which includes dry fuel plus water. Note, this is sometimes called an "as-is" basis.

$$\%MC_{wb} = (\text{water weight} / \text{sample weight}) \times 100 \quad (1)$$

Dry Basis (db) moisture content (MC) is the weight of water in the sample divided by the dry sample weight.

$$\%MC_{db} = (\text{water weight} / \text{dry sample weight}) \times 100 \quad (2)$$

The conversion between $\%MC_{wb}$ and $\%MC_{db}$ can be performed as follows:

$$\%MC_{wb} = (\%MC_{db} / (\%MC_{db} + 100)) \times 100 \quad (3)$$

and

$$\%MC_{db} = (\%MC_{wb} / (100 - \%MC_{wb})) \times 100 \quad (4)$$

⁴Black-out refers to the cessation of flaming combustion.

Both measures of moisture content are used widely in the literature with no definite preference shown.

The following describes effect of moisture on the performance of solid fuels by major topic as follows: 1) Heat Losses and Heating Value Analysis, 2) Volumetric Expansion, 3) Flaming Temperature, and 4) Rate of Combustion.

1) Heat Losses and Heating Value Analysis

This analysis draws heavily from the work given in [10]. Two energy loss terms are developed here: a) energy used to vaporize water formed during combustion, and b) the energy used to vaporize the "free" and "bound" water in the fuel, respectively.

a) Energy used to vaporize water formed during combustion

Let Q_{H_2} (Btu/hr) be the rate of heat loss due to vaporization of the water formed during combustion by the oxidation of hydrogen; then, Q_{H_2} can be calculated as follows:

$$Q_{H_2} = M_{H_2} * h_{fg} \quad (5)$$

where Q_{H_2} = rate of energy required to vaporize water at the reference state of 68°F, M_{H_2} = mass rate of water formation by combustion, $h_{fg} = 1055$ (Btu/lbm-H₂O) at 68°F. The lower heating value, as mentioned previously, can now be calculated as follows:

$$LHV = HHV - Q_{H_2}/M_{dw} \quad (6)$$

where, LHV = lower heating value (Btu/lbm-dry fuel), HHV = higher heating value (Btu/lbm-dry fuel), M_{dw} = mass rate of dry fuel into combustor. Note that Q_{H_2} is divided by M_{dw} to keep LHV on a "dry" basis consistent with the definition of HHV.

b) Energy used to vaporize the "free" and "bound" water in the fuel

The following discussion deals specifically with moisture in wood, yet, there is no reason why it is not generally applicable to any solid fuel that is porous. First, the distinction between "free" and "bound" water must be made. Bound water is formed by adsorption along the interface with cell walls and is rarely more than ten molecules thick. Adsorption is the take-up of water by chemical reaction, i.e. heat is actually evolved by adsorption, energy that later must be replaced if the water is to vaporize. Free water is formed by absorption. Absorption is a physical process, due to capillary action, of water take-up into the porous structure of a solid. There is only a very small emission of heat due to absorption and it is considered negligible compared to adsorption. There is always some water vapor in the porous cell structure of a fuel, but its effect is also considered negligible.

The moisture content of wood at which all the free water is gone but the bound water remains, is called the fiber saturation point (FSP). For wood, the FSP is approximately, $\%MC_{wb} = 21.9$. The energy required to bring the bound water to the energy level of the free water is not a constant, but a function of moisture content (below FSP). This function is different for every fuel and can only be determined experimentally. The equation for the average energy required to bring the bound moisture in Douglas Fir wood to the energy level of the free water, *not* to vaporize it is found in [10]. H_{bw} is this required energy and has the units of (Btu/lb). The equation for H_{bw} is a long polynomial expression from regression analysis and will not be copied here; however, Figure 2 shows the results.

It is now possible to define lower heating value two (LHV2), as LHV2 is simply LHV minus the energy required to vaporize all water carried in by the fuel, both bound and free. The expression for LHV2 is given as:

$$LHV2 = LHV - ((H_{bw} + 1055) * (MC_{db})) \quad (7)$$

Figure 2. H_{bw} or the Adsorption Energy versus Moisture Content (wet-basis). Source [10].

where LHV2 = lower heating value two(Btu/lbm-dry wood), H_{bw} = specific energy loss due to bound water(Btu/lbm-water), $1055 = h_{fg}$ (Btu/lbm-water), and MC_{db} = moisture content dry-basis(lbm-water/lbm-dry wood). Figure 3 shows the effect of moisture on the three heating values as defined above.

The energy required to vaporize the free water plus the bound water that has been brought to the energy level of the free water can be calculated as follows:

$$Q_{fw} = M_t * h_{fg} \quad (8)$$

Figure 3. The Effect of Moisture on the Heating Value(s) of Wood Biomass. Based on Douglas Fir with an Assumed Higher Heating Value of 8800 Btu/lbm.

where Q_{fw} = energy rate required to vaporize the free water and bound water that has been raised to the energy level of the free water, i.e. it is now "free" (Btu/hr), M_t = total mass rate of water brought in by the fuel, units are (lbm/hr), $h_{fg} = 1055$ (Btu/lbm-water), as usual.

In total, the rate of energy required to bring all moisture to the vapor state at 68°F is Q_{tot} , where:

$$Q_{tot} = Q_{fw} + Q_{H_2} + Q_{bw} \quad (9)$$

It should be noted that these losses occur *in* the combustion chamber. When vaporization is calculated or occurs at 68°F there is no change in gas temperature, thus, no increase in the available energy of the gases is realized. That is why this total heat of vaporization is considered a loss. However, boiler exhaust temperatures are usually on

the order of 400°F [38], and water vapor at 400°F and 1 atmosphere is superheated. This means that even more energy is lost due to combustion heat wasted on superheating vapor that is sent out the stack.

2) Volumetric Expansion

The effect of moisture on the volume of flue gases can best be understood by noting that water undergoes an expansion of approximately 5700 times its original volume when shifting states (liquid to a vapor) in the typical furnace operation [10,21]. An easy way to estimate this expansion is to look at the specific volume of water in the liquid state, v_f (ft³/lbm), at the reference temperature 68°F, then, find v_g (gaseous specific volume) in the superheat tables at atmospheric pressure and the desired/estimated maximum combustion gas temperature. Next, compute the ratio of (v_g/v_f) where this value is the expected volume expansion parameter. For example, data from [2] give as values for v_f and v_g :

$$v_f (68^\circ\text{F, sat.}) = .016 \text{ (ft}^3\text{/lbm)}$$

$$v_g (14.7 \text{ psi, } 1600^\circ\text{F}) = 83.47 \text{ (ft}^3\text{/lbm)}$$

so,

$$v_g/v_f = 5216.9 \text{ (vol.gas/vol.liquid)} \quad (10)$$

Note that this calculated value is close to the number cited above, and is primarily a function of the chosen superheat temperature.

The main problem associated with this enormous expansion is the associated increased gas velocity. Using the simplest form of the Continuity Equation, $Q = VA$, where Q = volumetric flowrate, V = velocity, and A = area, one can see that if Q is increased while holding the area A constant, the velocity V must increase proportionately.

There are a number of problems caused by increased gas velocities, especially if the furnace and/or boiler was not designed adequately for high moisture fuel. These problems are:

- 1) Reduced combustible gas and combustible particulate residence time, i.e. increased particulate carryover and unburned gases escape [3,11].
- 2) Increased erosion by particulate abrasion action, especially in high ash fuels [18].
- 3) Emission control devices cease to function properly if undersized for such volumetric and mass particulate loading. It may also be necessary to increase the size of induced draft fan motors to "keep-up" with the required flow [3,10,11].
- 4) There is a potential for increased flue exhaust gas temperature, thus, increased heat losses by sensible and latent enthalpies [11,21].

3) Flaming Temperature

The method of calculating adiabatic flame temperature by the "free energy minimization" method is described in [22]. Adiabatic flame temperature is the maximum temperature that can be achieved for a given fuel [22]. It is based on the theoretical concept of no changes in kinetic or potential energy of the reactants. All energy is released as heat. This condition is obviously never met in "real-life", but is very useful for comparing different fuels potential heat transfer properties, i.e. higher flame temperature means greater temperature gradients to drive heat transfer from gases to water in boiler tubes. Figure 4 shows the results of an analysis of the effect of moisture on the adiabatic flame temperature for Douglas Fir and Yellow Pine. It is interesting that the effect of moisture on flame temperature is almost entirely linear. If the percentage temperature decrease from 15 to 50 percent moisture is calculated for Douglas Fir and for 20 to 50 percent moisture for Yellow Pine the temperature decrease is 22 percent. That is, the flame temperature is decreased by 22 percent in both cases. This seems considerable, but the results might not be as dramatic in a "real" situation, due to many interrelated heat loss

Figure 4. The Effect of Moisture on the Adiabatic Flame Temperature of Yellow Pine and Douglas Fir Wood.

mechanisms [2]. This type of study will become more relevant as attempts are made to squeeze more and more energy out of wet fuel that has in the past been considered waste, i.e. hogged fuel being burned because it is cheaper than landfilling.

4) Rate of Combustion

Most of the combustion experiments examining the rate of burning have been carried out on small, usually cylindrical or cubic, single particles [13,23,24,25,26]. These tests are performed in very sophisticated devices where variables of temperature, mass loss, and composition, can be controlled and measured accurately. Tests such as these usually do not model spreader-stoker boilers, wood stoves, or dutch ovens, but the information is still useful, qualitatively, if not quantitatively.

A study on the effect of moisture on sugar pine and white oak under conditions meant to simulate a stoker-type furnace was reported by [13,26]. A single round particle was subjected to parametric variations in initial temperature, Reynolds number, oxygen concentration, moisture, wood type, and size (10 and 20 mm dia.).

The results of this study for moisture variation are very interesting. As one would expect, moisture does slow the rate of mass loss or burning. At zero moisture the peak reactivity is $.045s^{-1}$, at $13\%MC_{wb}$ it is $.031s^{-1}$, and at $71\%MC_{wb}$ the peak reactivity is $.018s^{-1}$. Reactivity in this case is defined as the time rate of mass loss divided by the initial mass, sometimes called the normalized reactivity.

For a saturated 10mm pine specimen, moisture = 71%wb, the normalized rate of burning or reactivity rises sharply to a short, constant plateau, then falls steadily until the end of the burn. Previous researchers had postulated that there would be very little combustion until the "free" water was evaporated [26]. The data from [13,26] do not support this. There was also direct visual observation of flaming to support the fact that combustion took place virtually during the entire experiment.

Figure 5 is an adaptation from [26] that shows the effect of moisture on normalized burning rate. A very similar study, but on 1.5 cm pine cubes at $1454^{\circ}F$, was performed [23]. The general result is the same, i.e. moisture slows the rate of burning. The data were displayed differently and it gives new insight to this problem. Figure 6 is adapted from [23]. It shows that the total burn time is virtually a linear function of moisture.

3.1.5 Bulk Density

Bulk Density is used to determine the heat content per unit volume of fuel or Q_v (Btu/ft^3). Q_v is used to compare different fuels heating values. There are two basic concerns:

Figure 5. Normalized Burning Rate (Reactivity) for a Pine Specimen at Different Moisture Contents.

Figure 6. Total Burning Time as a Function of Moisture Content for 1.5 cm Pine Cubes.

- 1) Will the feed system be able to carry the necessary volume of fuel to meet steam or heat load?
- 2) Can enough fuel be stockpiled to meet demand for extended periods? (Especially important for densified fuels which generally require protection from moisture or they will disintegrate.)

Q_v is determined as follows:

$$Q_v = HHV * D_b \quad (11)$$

where D_b = bulk density (lbm/ft³) and Q_v = volumetric heat content (Btu/ft³). D_b is determined by an ASTM technique requiring a container with a volume of one cubic foot (ft³) as the basis of measurement and accurate weighing. The ASTM Standard is No. E 873-82, "Bulk Density of Densified Particulate Biomass Fuels." Currently, a standard does not exist for nondensified biomass fuels.

Bulk Density is a requirement for the Association of Pellet Fuel Industries (APFI) Standard, No. APFI-PF-1-88 [27]. This standard requires a bulk density of 40 (lbm/ft³) for residential grade pellet fuel. The Fiber Fuels Institute (FFI), recommends a bulk density of at least 36 (lbm/ft³) [28]. Table 6, lists the high and low values of bulk density reported for various fuels.

3.1.6 Particle Size

Particle Size is important for two reasons. One is the effect of size on fuel feed systems. This is not as critical for belt/conveyor-type feeders, but is important for auger-type feed systems as found in pellet stoves. Auger systems are susceptible to bridging if the fuel is small enough to lodge between the auger tines and feed tube wall.

Secondly, particle size is important for combustion efficiency and erosion concerns. This is true for pelletized and as-is fuels, i.e. hoggèd wood, chips, RDF, etc.

Table 6. High and Low Range of Bulk Density for Selected Biomass Fuels. Sources [6,29].

Fuel Type	D_b (low) (lbm/ft ³)	D_b (high) (lbm/ft ³)
Wood (hogged)	10	20
Wood (pellet)	32	42
Wood (chips)	18	26
RDF (all classes)	1.9	12.8

"Fines" are any particle less than 1/4 inch [14]. There are two major concerns with the quantity of fines in a fuel source. First, since wood and RDF are usually 70 percent volatile matter or more, the rate of combustion is directly proportional to how quickly the required heat reaches and pyrolyses the volatile material [14]. The rate of heating is dependent on the exposed surface area per unit volume of the particle. Larger particles have a smaller ratio of surface area to volume and tend to insulate themselves progressively during combustion by formation of a char layer with low thermal conductivity [14,30]. Therefore, smaller particles are more reactive than larger particles. This increased rate of combustion requires greater air supply and this in turn can decrease efficiency by a number of mechanisms. These mechanisms are: a) greater flue gas temperature at exit, b) less particle residence time (especially the fines), and c) erosion due to increased gas velocities. Secondly, as particle size decreases there is an increased "dust" problem due to wind carried biomass. There is a greater fire hazard due to the explosive nature of fine particulate fuel.

3.1.7 Durability

Fuel pellet durability is a measure of a pellets propensity to produce fines while under physical agitation. At present, there is no ASTM Standard available; however, tests are currently being performed

which may become part of an ASTM Standard. Testing of pellets per the preliminary ASTM Standard requires the use of a tumbler of specific design, weighing apparatus accurate to .1 gram, and a standard set of Tyler sieves.

Procedurally the pellets are weighed into 250 gram samples and loaded into a tumbler (see Figure 7) and tumbled for 5 minutes at 50 RPM. The tumbler is then unloaded into the top of a set of Tyler sieves numbered 8, 14, 28, 48, 100, and 200 and shaken for a time of 3 minutes. When finished, the contents of each sieve and pan are emptied into separate preweighed containers. The contents retained in each sieve are weighed to the nearest 0.01 oz. The experiments are repeated 3 times for each sample.

Table 7 presents the listing of pellets tested and Figures 8 and 9 graphically compare the 16 different samples that were tested. Figure 8 plots the percentages of pellets remaining after tumbling (the more durable the pellet, the higher the percentage remaining). For example, sample 14 was the most durable of all the samples with 99.4 percent remaining as pellets. On the other hand sample 9 was the least durable with only 91.2 percent remaining pelletized. Figure 9 plots the percentage breakdown of the fines after tumbling. Again, sample 14 is the most durable, having the lowest percentage of fines. Figure 9 is useful in analyzing how the pellet breaks up. This information can be used to target areas for pellet improvement.

The purpose of durability experiments was to draw conclusions as to why some pellets hold together better than others. The different parameters explored include rape seed percentage, salt percentage, ash percentage, method of manufacture, and composition. Due to the small sample size it is not possible to present conclusions that are statistically significant although it is possible to look at general trends.

Rape seed is an oily agricultural waste used to help the pellet material plasticize and form into pellets. The comparison of rape seed

Figure 7. Pellet Tumbler for Durability Testing.

Table 7. Specifications for Pellets Tested for Durability.

Specie	Composition	Sample No.	Rape (%)	Salt (%)	Ash (%)	Method
FHLDF624-1	Pure Douglas Fir	1	1	0	0.21	NC PP
FHLDF624-2	Pure Douglas Fir	2	2	0	0.99	NC PP
PHCMX706-1	Douglas Fir/Red Alder	3	0	N/A	N/A	NC PP
PHCHF705-2	Pure Hem Fir	4	0	0.003	0.96	NC PP
EVCMX713-1	Red Alder/Hem Fir/Douglas Fir/Cedar	5	0.25	0	2.24	NC PP
WSPCD715-1	Pure Red Cedar at least 1 year old	6	0.25	0	0.61	NC PP
KMPMX727-2	Red Alder/Maple/Myrtle 4-5 years old	7	0.5	0	1.15	NC PP
SPCDF727-1	Douglas Fir	8	0.5	0.78	2.55	NC PP
WFPMX920-1	60% Hem Fir/40% Sitka Spruce	9	0.25	0.19	2.43	NC PP
HSIMX824-1	Cedar/Spruce	10	trace	N/A	0.7	NC PP
BCCPP824-1	Pure Ponderosa Pine No Bark	11	0	0.001	0.22	NC PP
BTPMX920-1	50% Pine/50% Fir	12	0	N/A	N/A	C RE
WDMMX920-1	60% Douglas Fir/40% Ponderosa No Bark	13	0	N/A	N/A	C RE
RMMMX920-1	60% Douglas Fir/40% Ponderosa No Bark	14	0	N/A	N/A	C RE
NWPM	Commercial Test Pellet	15				
NWPM10-5	NWPM Pellets After 10 Minute Tumble	16				

NC = Non-Commercial
C = Commercial
PP = Pellet Punch
RE = Rotary Extrusion

Figure 8. Pellets Retained After Tumble and Sieve Experiments Compared by Sample Number. (Pellet content is listed in Table 7.)

Figure 9. Breakdown of Fines After Tumble Sieve Experiments Compared by Sample Number.

percentages with all other factors held constant is shown in the comparison between sample 1 and 2. Both samples were pelletized out of the same raw material, pure Douglas Fir, but sample 1 contained 1 percent rape seed and sample 2 contained 2 percent rape seed. The tests indicate that sample 2 with higher rape seed formed a better pellet as expected.

Samples 8 and 9 were the lowest performing pellets and as indicated in Table 7 they contained salt and dirt which gives the highest ash contents. The low performance could be linked to the reoccurrence of the impurities. Method of manufacture seemed to have no significance on the durability of the pellets.

3.1.8 Specific Density

Similar to pellet durability, there is not a nationally recognized standard for measuring biomass pellet specific density. Specific density is a measure of a single pellets mass per unit volume, such as (lbm/ft^3). Biomass users are usually concerned with bulk density since they deal with quantities of fuel on a "macro" scale. Bulk density will help them size feed systems, design grates, and determine volumetric firing rates to maintain steam load, etc. Specific density is an important independent variable when it comes to single particle combustion kinetics.

Table 8 presents specific density information for 14 different pellets tested.

3.1.9 Ash Fusion Temperature

Four temperatures are currently used to specify ash fusion temperature as specified by standards such as ASTM No. D-1857, "Fusibility of Coal Ash." The four temperatures are:

- a) Initial Deformation Temperature (IT)
- b) Softening Temperature (ST)

Table 8. Physical Analyses Data for Pellets (1-14).

	HHV ^a (Btu/lbm)	MC ^b (%)	BLKD ^c (lbm/ft ³)	SPD ^d (lbm/ft ³)	Length (in.)	Diameter (in.)
MIN	8637.99	3.40	37.21	75.32	.266	.256
MAX	9284.34	14.40	53.34	83.92	.705	.317
MEAN	8721.26	6.98	41.84	81.26	.464	.287
SDEV	93.65	1.81	11.83	4.04	.174	.078

^aHHV = Higher Heating Value

^bMC = Moisture Content (wet-basis)

^cBLKD = Bulk Density

^dSPD = Specific Density

c) Hemispherical Temperature (HT)

d) Fluid Temperature (FT)

These definitive terms refer to the shape of a specified cone of ash as it is subjected to increasing temperature under "standard" conditions. This test can be performed in an oxidizing and/or reducing environment.⁵ This is important depending on which environment the ash will be in. Furnaces operated at low excess air level or with poor mixing would create local reducing environments. Table 9 gives the ash fusion (fluid) temperatures for a number of species in oxidizing and reducing environments.

Table 10 lists the range of ash fusion data for the pellet samples.

It is interesting to note that the mean initial ash fusion temperature is only 1.7 percent smaller than the mean fluid temperature. Also, the average difference between MIN and MAX values is only 361°F,

⁵Examples of oxidizing and reducing reactions are shown in Figure 15.

Table 9. Ash Fusion Temperatures for Selected Species of Biomass Fuels. Sources [7,28,31].

Species	Ash Fusion Temperature (fluid)	
	Oxidizing (°F)	Reducing (°F)
ASTM Rank hvA coal	Unav.	2660
ASTM Rank subbit.C	Unav.	2310
RDF (range)	2200 – 2420	2160 – 2340
Wood (avg)	2390 ^a	2410

Table 10. Ash Fusion Data for Fuels (1-9).

	Ash Fusion Temperature (oxidizing, °F) ^a			
	Initial	Softening	Hemispherical	Fluid
MIN	2150	2160	2170	2195
MAX	2500	2530	2540	2550
MEAN	2340	2352	2363	2381
SDEV	136	137	138	141

Note: All data are on a (dry-basis).

^aThe various ash fusion temperatures (Initial, Fluid, etc.) refer to the increasing "flatness" of a specified cone of ash as it experiences increasing temperature. "Initial" is least deformed and "Fluid" is when the ash appears molten.

not a significant amount considering the temperature variations associated with combustion in a furnace.

3.2 Municipal Solid Waste (MSW) and Refuse Derived Fuels (RDF)

In the five-state Pacific Northwest region being studied, it is estimated that over 18,000 tons per day (TPD) of MSW are generated. Eleven million Btu/ton of MSW is equivalent to over 32,000 Bbl (barrels) per year of fuel oil. For local estimates of fuel availability, an average of 4 lbs per person per day [32] should be used, with this value expected to continue to increase in the future. This is a considerable amount of energy, much of which is being discarded in landfills.⁶

The American Society for Testing and Materials (ASTM) have classified the different types of RDF into seven categories ranging from raw MSW to the combustible portion being gasified. Varying degrees of processing may be desired based on the intended method of combustion, the environmental concerns, and the recovery of valuable recyclable materials.

Of the present technologies for converting MSW to useful energy, the most prevalent are mass burning of MSW or firing RDF in either fluff or pellet form. Each of these technologies require different degrees of processing. Each method is designed to balance the cost of preparation against the need to minimize environmental impact and maximize the Btu yield.

Items segregated prior to mass burning MSW include tires (due to their high sulfur content), large, noncombustible items, and infectious medical wastes. Ferrous metals in the waste can be recovered from the

⁶Legislative priorities for solid waste management are: 1) waste reduction; 2) resource recovery/recycling; 3) energy conversion; and 4) disposal.

ash by magnetic separators, and then sold as scrap. Some advantages of mass burning MSW are:

- little or no fuel preparation;
- technology is well proven (25 years USA and Europe);
- lower operating noise levels;
- lower maintenance;
- grate systems allow for cofiring of coal and sludge waste from sewage plants; and
- plant size can be minimized (no fuel processing equipment is necessary).

Some disadvantages of mass burning are:

- increased corrosion (high temperature, erosion, condensation in the stack);
- slagging and fouling; and
- nonuniform heat input.

RDF fuels require extensive processing involving the separation of combustible components from noncombustible components. Figure 10 shows a typical flow diagram for processing RDF. The process may be supplemented by varying degrees of mechanical or manual sorting to recover recyclable materials. For example, Reuters commercial RDF plant in Eden Prairie, Minnesota uses extensive manual labor to recover recyclable materials. They claim that the sale of the recyclable materials alone pays for virtually all of the plant's labor costs. Additional revenue comes from the sale of RDF pellets at \$45 per ton, which is competitive with coal.

Some advantages of burning RDF are:

- removal of slag-forming materials;
- more rapid and better combustion;
- RDF may be cofired in existing coal burning boilers;
- RDF may be stored;
- more heterogeneous fuel;

Figure 10. RDF Processing Flow Diagrams.

- reduced corrosion problems;
- recyclable material is recovered; and
- power plants have greater reliability.

Some disadvantages of burning RDF are:

- higher fuel processing costs;
- processing plants have a lower reliability; and
- shredder explosions are not uncommon.

Pelletized RDF has all the advantages (and disadvantages) of burning RDF as listed above, but also supports improved fuel handling characteristics and allows for extended storage. After being pelletized, RDF can be cofired in coal plants using the spreader-stoker boilers having traveling or vibrating gates. It has been found that pellets can be burned successfully with little effect on the performance of the boiler. Boiler efficiencies have been found to drop by 2 to 6 percent [33,34], however, because of the higher moisture content of the pellets relative to the coal.

Some problems have been experienced during the storage of pellets. These problems include pellet breakage and reduction of the heating value with long term storage. During storage internal pile temperatures tend to increase. In one case, although the increased temperature did not result in pile ignition, the plastic covering ignited after ten months of storage.

For the conversion of waste to energy in electric power plants using dedicated boiler technology, mass burning is, on a large scale, the most cost effective method to produce low electricity costs. As the costs of electricity increases, coarse RDF technology becomes more cost effective. For cofiring, the mechanically prepared fluff is the most cost effective [34]. Problems associated with cofiring RDF in retrofitted boilers, such as boiler slagging and fouling, and reduced emission control equipment efficiency, have shifted interest from using modified existing boilers to cofiring RDF in boilers specifically designed for this purpose.

On a small scale, facilities that generate between 10 and 200 TPD of refuse and also require steam or hot water, can use on-site combustion to reduce the volume of waste generated and reduce fuel costs. Commonly used technologies include fluidized bed combustors (FBC) (150-200 TPD), rotary kilns (150-200 TPD), excess air grate systems (>75 TPD), and modular starved air systems which can burn as little as one TPD. These small scale technologies should be of interest to

institutions such as universities, hospitals, correctional facilities, and industrial sites as a solution to their waste problem, while reducing heating bills.

3.2.1 Fuel Classification, Higher Heating Value and Moisture Content

Prior to any decision making as to whether a waste-to-energy facility will be feasible, the fuel characteristics and availability must be known.

To classify the Pacific Northwest fuels, MSW samples from each of the five states were collected to determine their composition, HHV and moisture content. Upon receipt the samples were hand sorted into eleven categories, then a representative sample from each of the combustible categories was weighed and dried to determine individual and overall moisture content and the higher heating value. Sample data for Tacoma, Washington, are presented in Figure 11 and Table 11. Additional data for other cities is presented in Appendix C. One sample each of RDF fluff from Tacoma, Washington, and RDF pellets from Fairbanks, Alaska, were received and tested. Moisture analysis was performed on the fluff and pellets and found to be 38.3 percent and 6.3 percent, respectively. Additionally, the higher heating value (HHV) of the pellets were measured and an average value of 8400 Btu/lb was determined. This is also a good approximation for RDF since the pellets were formed from RDF using pellet presses. RDF pellets were not tested in the combustion unit due to the oversize pellet size. It should be noted that these are average heating values and that the actual energy content values may vary somewhat depending upon the season and the amount of processing done.

Figure 11. Composition of MSW from Tacoma, Washington.

Table 11. Moisture Content, Percent by Weight, and Heating Values for MSW as Received from Tacoma, Washington.

Tacoma, WA	Percent by Weight	Percent Moisture	HHV (Btu)	
			Low	High
Food Waste	.61	72.38	50.62	50.62
Lawn/Garden	3.30	58.14	264.78	274.01
Glass	0.49	—	—	—
Wood	7.08	21.24	490.24	730.30
Rocks/Ash	0.00	—	—	—
Paper				
Recyclable	20.29	31.21	1564.74	1721.80
Nonrecyclable	9.36	23.04	513.16	1098.76
Corrugated	3.27	42.15	242.73	242.73
Metals	7.73	—	—	—
Plastics/Leather	30.67	43.64	2415.36	6105.49
Textiles	17.19	38.23	1253.41	2346.93
Totals	100.00	36.70	6795.05	12750.64

4.0 COMBUSTION OF BIOMASS FUELS

Much of the available literature on biomass combustion deals with the thermochemistry of burning wood. The following material discusses the fundamental relationships and processes as presently understood.

Biomass combustion is a complex phenomena by which a solid fuel is thermochemically oxidized producing heat and gaseous by-products. Three main steps in biomass combustion [35] are: 1) drying, 2) pyrolysis and flaming combustion, and 3) fixed carbon combustion. It should be noted that in a fuel bed, such as found in a spreader-stoker or dutch oven, these three processes are occurring simultaneously, but in different locations.

1) Drying

Since most biomass fuels contain water, drying is a critical step. Free and bound water must be evaporated before sufficient temperatures for steps 2 and 3 occur.

2) Pyrolysis and Flaming Combustion

Pyrolysis is the chemical degradation of a solid fuel, due to heating, that produces char (fixed carbon) and combustible vapors (volatiles). Pyrolysis consists of endothermic⁷ and exothermic⁸ stages.

For wood the endothermic stage has two distinct temperature ranges [9,19]. For temperatures less than 392°F, water vapor, formic acid,

⁷Endothermic: A process or change that takes place with absorption of heat and requires high temperatures or initiation and maintenance. An example is production of carbon monoxide and hydrogen by passing steam over hot coke.

⁸Exothermic: A process or chemical reaction which is accompanied by evolution of heat, for example, combustion reactions.

and acetic acid are released from the fuel. For temperatures between 392°F and 536°F, water vapor, carbon dioxide, carbon monoxide, and a number of organic acids are released. This is the "slow pyrolysis" phase where largely noncombustible gases are formed [36].

The exothermic stage of pyrolysis occurs between 536°F and 932°F [9,19]. This is the "fast" or "active" pyrolysis zone. Highly flammable gases such as carbon monoxide, methane, aldehydes, methanol, and hydrogen are released, also, highly flammable tars remain in the solid phase as residue.

When sufficient oxygen and heat is present, the volatile components released during the fast pyrolysis will burn in flaming combustion. This provides a source of heat to continue the pyrolysis (heat the solid) and increase the overall rate of reaction.

3) Fixed Carbon Combustion

Fixed carbon combustion, also known as glowing combustion, is an exothermic process occurring at temperatures above 932°F [9]. This type of combustion is typically recognized as charcoal briquets used in a barbecue. For most biomass, fixed carbon represents only 10 to 20 percent of the solid fuel. However, this fixed carbon combustion acts as the primary source of heat for the raw (cold) fuel that is usually added on top of the fuel pile in grate-type systems. Glowing combustion releases enough energy to vaporize moisture and volatiles in hogged wood fuel with up to 50 percent (wet-basis) moisture content [35]. The energy from flaming combustion is not needed to dry the fuel [35].

4.1 Combustion Model and Efficiency

In its simplest form the burning of biomass fuels can be considered as the combustion of only carbon and hydrogen. The reaction equations for the oxidation of carbon and hydrogen are:

Equations (12) and (13) adequately describe the overall combustion process if the process is 100 percent thermally efficient and there are no other combustible elements such as sulfur and nitrogen. Since sulfur is sometimes present in biomass fuels it may be necessary to include the following equation for the oxidation of sulfur to sulfur dioxide:

When combustion is 100 percent efficient it means that all combustible elements have been fully oxidized to products releasing the greatest possible heat energy. For biomass fuels this implies that all carbon has been converted to carbon dioxide and all hydrogen to water. Maximum temperature will correspond to this point because optimum efficiency corresponds to reactions with the greatest heat release per pound of fuel.

Combustion or flame temperature in "real-life" burners will always be less than the calculated adiabatic flame temperature (AFT), because of heat losses. These losses include: 1) incomplete carbon and hydrogen oxidation; 2) combustion less than instantaneous; 3) radiation, convection, and conduction losses; and 4) inherent ash heated in the burner.

Combustion is never 100 percent efficient in actual burners. Another indication of this is the amount of carbon monoxide (CO) in the

exhaust. Remember that one product of fast pyrolysis and possibly even glowing combustion is carbon monoxide. If this CO is not later oxidized to CO₂ during combustion then it exits the burner as a heat loss. This loss is equal to 4340 Btu per pound of carbon in the fuel [10]. This is true because the oxidation of CO to CO₂ releases 4340 Btu/lb by the following equation:

Gaseous products of slow and fast pyrolysis contain unburned hydrocarbons and organic compounds, which for any number of reasons are not broken down and completely oxidized. They include hydrocarbons, and a wide class of organic compounds called polycyclic organic matter (POM) [38]. These emissions can be substantial in low efficiency burners such as wood-stoves that are "stoked or damped-down" and other poorly designed combustion equipment. In most commercial and newer residential appliances there is not significant heat loss from these unburned emissions.

Figure 12 is a schematic representation of the primary processes that occur in a fuel bed such as found in a spreader-stoker or dutch-oven-type furnace. The curves to the right of the picture and text show how combustion gas composition and temperature vary with height in the fuel bed. Figure 12 shows approximately where the idealized combustion equations [Eqs. (12), (13) and (15)] occur within a fuel bed. Note that this is a schematic representation and the actual distribution of where the combustion reactions occur depends on many things; some are, percent excess air, ratio of over to underfire air, and fuel moisture content.

Another widely used measure of combustion efficiency is the combustible material remaining in the ash that leaves the burner with the exhaust gases (called fly ash) [39]. This ash usually contains

Figure 12. Schematic Representation of a Fuel Bed and the Basic Chemical Equations for the Combustion of Solid Biomass Fuel, including Composition and Temperature Plots. Source [38].

inorganic (non-combustible) and organic (combustible) particulate. If the combustion were 100 percent efficient there would be no combustible in the fly ash, it would be burned to CO_2 and/or H_2O .

Oxides of Nitrogen - Another indicator of combustion efficiency is oxides of nitrogen. The presence of oxides of nitrogen (NO_x) in the exhaust gases may prove to be a useful indicator of combustion temperature. Usually, NO_x is discussed for its contributing role in photochemical reaction in smog production [38,40]. However, it is well known that NO_x formation is catalyzed by increasing temperature, and as was discussed earlier, increasing temperature signifies increased combustion efficiency.

There is a complicating factor for solids combustion. It is that NO_x can be formed in relatively substantial quantities by both air-born and fuel-bound nitrogen. In well-mixed, flaming combustion NO_x should peak at the stoichiometric air/fuel ratio, but because of "kinetic nonequilibrium"⁹ effects, it is found in a slightly oxygen rich environment [40]. The NO_x formed by air-born nitrogen is sometimes called "thermal NO_x " because its formation is highly temperature dependent, but it also depends on local oxygen concentration.

Nitrogen in fuel is usually bound to hydrogen or carbon atoms and is sometimes called "chemical NO_x " when it is burned. Experiments have shown that when fuel nitrogen compounds are present the overall NO_x level can significantly increase. Most interesting though is that fuel bound NO_x formation seems to be only slightly temperature dependent as opposed to the strong temperature dependence of thermal NO_x formation [40]. Fortunately (from an air quality standpoint), fuel-bound nitrogen is usually a very small percentage by weight of the elemental components of biomass fuel i.e. ≈ 0.0 to 1.0 percent.

⁹Kinetic nonequilibrium refers to a partially complete time-dependent chemical reaction.

4.2 Environmental Considerations

Gaseous emissions and other pollutants are currently regulated by Federal, State or local agencies. No attempt is made to cite exact emission standards for all possible situations. This is a very complex subject which depends on many factors, including:

- 1) Type of appliance
 - a) residential wood stove
 - b) commercial/institutional boilers
- 2) Size of appliance (heat or steam rating)
 - a) Btu/hr
- 3) Fuel used
 - a) coal, oil, natural gas
 - b) cofired; coal + wood etc.
 - c) RDF/MSW
- 4) Regulatory Agency
 - a) area where appliance is situated
 - b) time of year
 - c) air quality at any particular time

Information on emission standards specific to a particular installation, can be obtained from the Environmental Protection Agency (EPA), Federal Register, or individual State Environmental Agencies.

Emission regulations are enforced by three levels of government: Federal, State and local. The Federal agency in charge of setting standards and enforcing them is the Environmental Protection Agency (EPA). The EPA sets the standards for type of emission, sampling method and emission level. The State agencies (such as Oregon's Department of Environmental Quality DEQ), and local agencies, are really the workhorses in the program. Their job is to provide a permitting

process and make sure the EPA standards are met or exceeded, i.e. each State has authority to raise the emission level standard above that required by the EPA, but they may not provide variance for lowering those standards.

Table 12 lists the EPA criteria and noncriteria emission species for wood fired appliances. "Criteria" species refers to emissions that are regulated by law and noncriteria species are those that are not regulated at present but are being studied extensively for possible inclusion. It should be noted that the criteria emission species listed in Table 12 are enforced at some level for all combustion devices including those that burn coal, oil, RDF and other biomass fuels. Following is a brief description of each criteria emission.

Particulate - This is the fine liquid or solid particles that exit the furnace stack. It consists of combustible, organic and non-combustible (ash) material. The standard for sampling particulate is EPA Method 5. In many instances this is the only emission requirement necessary to meet state certification. Along with particulate, some areas have opacity¹⁰ standards which limit the amount of visible smoke emissions [3].

Sulfur Oxides (SO_x) - SO_x is formed by oxidation of fuel bound sulfur during combustion. Sulfur content in wood fuel is usually so low that SO_x is immeasurable, however, this may not be the case with MSW/RDF fuels or in coal + biomass cofiring applications. The applicable standard is EPA method 6. Some work suggests that even in bark combustion with relatively high sulfur content most of the sulfur (approximately 95 percent) remains in the ash [19].

Nitrogen Oxides (NO_x) - Most licensing agencies do not regulate NO_x emissions. This is due to the fact that most local areas are not subject to the atmospheric conditions leading to photochemical smog.

¹⁰Opacity is the degree to which emissions reduce the transmission of light and obscure the view of an object in the background.

Table 12. EPA Criteria and Non-Criteria Emission Species for Wood Burning Devices. Source [38].

Emission Species	Criteria	Non-Criteria
Particulate	*	
SO _x	*	
NO _x	*	
Hydrocarbons	* ^a	
CO	*	
Condensable Organics		*
POM ^b		*
Formaldehyde		*
Total Carbonyls		*
Phenol		*

^aTypically there is a Primary Ambient Air Quality Standard (PAAQS) set for all criteria emissions; however, none exists for hydrocarbons [38]. Some states do have a standard for hydrocarbons.

^bPOM = Polycyclic Organic Matter

It should be noted that there are no NO_x pollution abatement methods (no devices) that can be employed "on-line" in the exhaust stream. Only by reduction of flame temperature can NO_x formation be decreased [7]. Operating at low excess air levels, using low-turbulence diffusion flame operation and using water cooled furnaces helps control NO_x formation.

Carbon Monoxide (CO) - CO formation is a result of poor combustion. It can be a serious problem in boilers fired with wet fuel because it is caused by low combustion temperatures, especially in the flaming combustion zone where much of the CO is converted to CO₂ in

furnaces using overfire air. CO emission tests are not always required by regulatory agencies, but it is much more widely tested than NO_x.

Hydrocarbons - Hydrocarbons are volatile gases that result from the incomplete combustion of both the carbon and hydrogen in fuel. Usually they result from incomplete pyrolysis and combustion of large chain volatiles such as cellulose and formaldehyde [9]. Similar to carbon monoxide, hydrocarbon emissions are not usually a test requirement to meet state licensing laws.

The entire field of combustion technology and environmental standards for RDF/MSW is in a rapidly, growing stage. Table 13 shows the current National Ambient Air Quality Standards (NAAQS) for any device (including furnaces) which emit such pollutants.

In addition to the NAAQS, another set of standards called National Emission Standards for Hazardous Air Pollutants (NESHAP) comes from the Clean Air Act Amendment of 1977 (CAAA). NESHAP regulates emissions for which no NAAQS exists. At present the EPA has designated: asbestos, beryllium, mercury and vinyl chloride as hazardous air pollutants [41].

In most locations for solely wood-fired furnaces of institutional or commercial size there are no ash handling standards similar to the EPA regulations for gaseous emissions. Many wood product industry boilers in the five-state Northwest Region use the ash for roadfill. However, for coal, RDF, or MSW furnaces there are EPA standards. Many utility size boilers both coal, cofired, or pure RDF/MSW fired, use water to quench and transport collected grate and fly ash.

Where sitting conditions permit, ash slurry is pumped to holding ponds where the process may include water recovery and reuse [7].

For RDF/MSW or cofired plants, the EPA requires that bottom ash be tested for the heavy metals listed in Table 14.

Table 13. National Ambient Air Quality Standards. Source [41].

Emission Species	Averaging Period	Primary Standard (mg/m ³)
Sulfur Dioxide	24 hr	365
Total Sus. Particulate	24 hr	260
Carbon Monoxide	8 hr	10,000
Photo-Chemical Oxidants	1 hr	240
Nitrogen Dioxide	Annual mean	100
Non-Methane Hydrocarbon	3 hr	160
Lead and its compounds	1 calendar quarter	1.5

Table 14. EP Toxicity Parameters and Current Maximum Allowable Levels. Source [42].

Metal Contaminant	Max. Allowable Concentration (milligrams/milliliters)
Arsenic	5.0
Barium	100.0
Cadmium	1.0
Chromium	5.0
Lead	5.0
Mercury	.2
Selenium	1.0
Silver	5.0

The trace metals Antimony, Beryllium, Copper, Nickel, Thallium, and Zinc, are also under intense scrutiny as possible contaminants to add to the EP Toxicity list [42].

4.3 Equipment Considerations

4.3.1 Ash

Ash from biomass fuels is the single most destructive constituent for furnaces and boilers. The three main problems with the ash in fuel are:

- 1) Slagging/Deposition
- 2) Erosion
- 3) Corrosion

Slagging occurs when ash becomes softened or liquid and clings tenaciously to grate, ceramic and waterfall surfaces. "Slagging" is a term that is widely misused to describe two distinct entities. Slagging is defined as fused matter or re-solidified molten ash that forms on furnace walls or other surfaces exposed mainly to radiant heat or very high gas temperatures. Deposition is the process where cemented or sintered ash builds up usually on convection surfaces such as superheater and re-heater tubes, but can also form on cooler furnace surfaces.

The major problems with slagging and deposition is that it reduces heat transfer on heat exchange surfaces, and can bridge, plug and mechanically destroy grates. Slagging and deposition can tear down refractory by repeated liquidizing and re-solidification.

Erosion of furnace and boiler surfaces is largely due to dense, hard, particulate ash which is in the gas stream. It is an important topic because erosion can be rapid if the right conditions exist of high ash concentration and high exhaust velocities.

Corrosion has been studied intensively by the coal furnace and boiler industry. It is also gaining rapid attention in the cofiring and RDF/MSW industry because of the highly corrosive nature of the constituents in RDF and MSW. The major problem with corrosion is metal wastage.

For salt-soaked wood fuel and RDF/MSW chlorine can cause severe metal wastage. Chlorine in refuse is responsible for the most serious corrosion of boiler tubes [4]. Sulfur, Sodium, potassium, lead and zinc also do their share.

An extensive study of chloride corrosion from the burning of both RDF and MSW cofired with high sulfur coal provide the following conclusions [4]:

- A) The conversion of chlorides to sulfates in ash deposits by the action of SO_2 releases chlorine and hydrochloric acid at the metal surfaces. This causes serious corrosion.
- B) Chloride corrosion can be made negligible by increasing the available sulfur in fuel to equal 2 percent by weight of the refuse.
- C) Cofiring of MSW with high sulfur coal for up to a 60/40 blend (Btu basis) will not increase the initial corrosion rate beyond that of coal alone.

Points B and C above are interesting and potentially valuable. There are two major benefits to cofiring high sulfur coal, MSW/RDF, or salt soaked wood biomass. One benefit is that decreased high-sulfur coal input means less sulfur oxide emissions and subsequently less acid gas emission, i.e. H_2SO_4 , one component of "acid-rain". The other benefit is that metal wastage by chloride corrosion is reduced significantly, helping reduce maintenance and material cost.

Figure 13 shows the isothermal corrosion rate in (mils/hour) vs. sulfur addition to refuse (MSW). The figure indicates that for sulfur additions less than .75 percent the result is generally increased corrosion, yet, beyond .75 percent there is a dramatic corrosion

Figure 13. Isothermal Corrosion Rates as a Function of Sulfur Addition to Municipal Solid Waste. Source [4].

reduction. The gaseous emissions were not included in this study, so a judgment can not be made of the relative merit of corrosion inhibition vs. emission quality. The overall idea seems worthwhile and more studies should be done.

Conclusions from a second study on corrosion problems for refuse-type fuels indicates that lead and zinc in the form of chlorides of lead sulfates and chlorides of zinc, contribute to the corrosion in power plants.

It is apparent that ash is a destructive element in operating furnaces and boilers and may also be a toxic or harmful environmental disposal problem. Wood fuels, in general, will cause fewer problems because of their low ash content, low heavy metal and usually low

chloride concentrations. MSW/RDF fuels can cause significant problems due to their overall ash content and chemical nature.

4.4 Methods of Combustion

There are many methods used to release the usable heat in the waste fuels to produce usable power, however, there is considerable confusion as to the classification of the methods of waste incineration. In the first method of classification, the differing combustion systems are broken down into two categories according to the types of waste fuel they use, which are: 1) mass-burning systems which can take raw MSW with minimal front-end processing, and 2) RDF systems which use RDF alone or cofired with another fuel such as coal or wood. The second classification method breaks down the combustion system according to the actual process of combustion, which are: 1) excess air systems which use an above-stoichiometric¹¹ amount of combustion air to fully fire the wastes, and 2) starved air systems which use a below-stoichiometric amount of combustion air to drive the combustible gases off the waste in the primary chamber and then the gases are ignited in a secondary chamber.

4.4.1 Excess Air Grate Systems

This is by far the most popular method for combustion among the large and intermediate power producing facilities that are servicing the waste disposal needs of a municipality. These systems are almost exclusively used as mass-burning units to accept MSW that is unprocessed (or has had very little processing). These systems are versatile and can accommodate other kinds of fuels for cofiring such as coal or wood.

¹¹Stoichiometric mixtures have the exact amount of oxygen to produce a complete combustion reaction.

The most popular of these grates is the inclined stoker grate that agitates the MSW for full burning as it travels down the grate. Figure 14 shows how the inclined stoker grate works to fully combust the fuel. The raw MSW is fed in at the top. It then rolls down under the force of gravity as the reciprocating grate sections agitate the fuel, exposing the unheated portion. Underfire air is fed in through slits in the grate and overfire air is fed in over the rolling mass. As the fuel travels down the grate, it goes through all processes of combustion. At the end of the grate, the fuel has been completely burned and the ash is removed.

The rotary kiln is used to agitate the fuel by turning it in a horizontally inclined drum which acts as the agitating grate. The fuel (which can be MSW or RDF) is fed in at the top of the drum and it goes through similar combustion processes as the inclined grate. The ash is removed at the bottom end of the drum and the hot combustion gases are directed into the heating elements of the boiler. Figure 15 is a simplified drawing of a rotary kiln. Unlike the inclined grate, the rotary kiln is generally limited to smaller scale operations. The most

Figure 14. Simplified Drawing of the Inclined Stoker Grate.

Figure 15. Simplified Drawing of a Rotary Kiln Combustor.

popular version of the rotary kiln is the O'Conner rotary combustor [33].

4.4.2 Modular Starved Air Systems

The modular starved air system burns MSW or RDF in a two-step process. In the primary chamber, the fuel is heated (pyrolyzed with below-stoichiometric or starved air) to drive off the combustible and other volatile gases. The combustible gases are pulled via an induction fan into the secondary chamber where actual ignition takes place with above-stoichiometric (excess) air. Figure 16 shows a simplified cross-sectional view of a typical modular incinerator.

4.4.3 Fluidized-Bed Combustion

Fluidized-bed combustion (FBC) is a relatively new technology that was developed for the combustion of coal. This method of waste-to-energy is still in its stages of development. Presently, there are

Figure 16. Simplified Cross Section of a Modular Starved Air Incinerator.

only a handful of commercially operated FBC facilities. These facilities are primarily used as on-site waste-to-energy systems for intermediate users such as universities or industrial plants [32].

The waste fuel can either be burned directly or it can be gasified (at starved air conditions) for use in a gas turbine. All FBC systems require that the input fuel must be relatively clean, and in the case of waste fuels, this means that only RDF can be used.

The FBC combustor works by having the RDF introduced on the "bed", which is a grate with air flow from underneath. This air flow actually suspends the fuel above the grate allowing for even agitation and combustion. About 15 to 20 percent of the fuel is actually "burned"; the remaining fuel is pyrolyzed under starved air conditions with the combustible gases being vented off the top of the FBC reactor. The combustible gases are then cleaned for use in a gas turbine or in a boiler.

4.4.4 RDF Cofired or Used Alone in Existing Boiler Designs

This is by far one of the most promising methods of waste-to-energy because the waste fuel can be used in boilers that currently burn other solid fuels, namely coal. In most cases, the processed RDF has a heating value that is similar to coal and can replace and/or supplement coal in existing boilers [43]. The opposite is also true: coal can be used to replace or supplement RDF in boilers that were built for RDF burning. RDF can be produced on-site, which is usually the case for facilities that produce and sell power; or the RDF can be produced off-site in a separate facility and then sold to individual users as a replacement fuel for coal. The potentially large market for RDF as a replacement fuel, especially among institutional and industrial boiler operators, has sparked the growth of an industry of commercial RDF producers.

4.5 Cofiring

Cofiring is generally considered to be the combustion of biomass with coal, but it may also be the concurrent firing of two dissimilar biomass fuels such as wood and RDF. Currently published cofiring experience is limited to large scale steam and electric plants. The reason for this is that electric utilities have been studying and using biomass as a real supplement to their normal coal fuel since the early 1970's. The attractiveness of biomass as a utility fuel is a function of the price of fossil fuels, the technology base (especially for retro-fitting), and system economics. Two main sections follow, one is on the positive aspects of utilizing biomass for cofiring and the other section discusses the negative aspects as they have been determined by utility experience.

4.5.1 Positive Aspects

One of the best reasons for utilizing biomass is the price compared to fossil fuels. Also, the price of most biomass fuels has not

increased as rapidly as fossil fuels [29]. However, biomass fuels are sufficiently available in most localities to completely supply large utilities and that is why cofiring is of importance. Although there does not seem to be an eminent danger of a shortfall in primary energy, i.e. coal, nuclear, and oil, it is a possibility and another motivation for at least studying cofiring. Conversely, in many areas of the U.S. there is a windfall of biomass, so much in fact that it is a real disposal problem. For example, Portland Oregon, has recently performed some rapid economic, societal, and political planning to determine what to do when their current landfill becomes inoperable. The final decision is to truck their waste outside of the Portland Metro area to a new landfill. Whole geographic areas may be affected, such as Southeast Alaska, where both MSW and wood biomass pose real disposal problems. The two main reasons for this are the fact that most of Southeast Alaska is public land and the areas that are private are unsuitable for landfilling (it is hard rock). The State of Alaska also maintains emission standards that exceed the Federal requirements in some cases.

A major reason for using biomass is to ameliorate the impact of strict environmental regulations. Biomass can help because it has been shown to be cleaner in use than high sulfur fossil fuels [29]. One major problem in burning coal is its sulfur content. Coal sulfur content ranges from .5 to 5 percent by weight, and generally, 90 percent or more of this will be converted to sulfur oxide pollutants. These pollutants are primarily sulfur dioxide SO_2 , with 1 to 4 percent sulfur trioxide SO_3 [7]. Wood and RDF have sulfur contents that range from 0.0 to .1 percent and .1 to .6 percent, respectively [6,7]. Obviously, the use of wood and/or RDF as additives to coal will decrease the overall output of sulfur oxides on a per-Btu-fired basis.

The production of biomass may also be less destructive to the environment, i.e. mill residues, tree and seed farms, and RDF processing plants, *versus* strip mining, nuclear waste disposal, and the catastrophic dangers of pipeline or tanker rupture.

The presence of biomass processors in a local area that can act cooperatively is a site-specific advantage for cofiring [29]. A study was completed of cofiring wood chips with coal in interior Alaska [12]. An interesting problem was noted; they would like to clear more land for agriculture and thin many stands of existing timber, but it is not economically advantageous at present. Currently, the practice is to pile and burn the biomass but this is expensive since it requires repeat piling and burning up to four times to sufficiently reduce the volume [12]. A complete technological and economic study was completed for Fort Wainwright, Alaska, to assess the feasibility of using wood biomass with coal to produce steam. The Fort Wainwright tests led to the following technical and economic conclusions, respectively.

4.5.2 Technical Feasibility

Burning wood chips with coal for producing steam is technologically feasible. The major problems were in fuel handling prior to burning and in meeting peak demand. One problem was mixing, but through trial-and-error the Fort Wainwright group found a suitable solution. Another problem was inadequate chip hopper volume and freezing. Both of these problems could be dealt with by a minor investment in storage technology.

The last major problem was meeting peak steam load. The stoker at Fort Wainwright was incapable of feeding enough fuel above an 80 percent coal + 20 percent chip mixture to keep steam rates at desired levels. This was mainly associated with the Fort Wainwright boiler and could be eliminated with a high volume stoking system [12]. Desirable facets of the operation were emissions all well below the State of Alaska Standard of .1 grams per dry standard cubic foot for coal burning installations operating before July 1, 1972. There was also an 8 to 16 percent reduction in bottom ash.

4.5.3 Economic Feasibility

As long as delivered wood chip moisture content is below 45 percent wet-basis (and all chips during testing were less than 41.6 percent moisture), all harvesting scenarios considered would result in a cost less than coal per Btu. However, the harvesting scenarios all assumed annual production of more than 20,000 tons of chips. With diminished output the harvesting would become economically infeasible. Unfortunately, the Fort Wainwright plant could, at best, only use approximately 50 percent of this 20,000 tons of chips. One or more utilities using wood chips would solve this problem. The Fort Wainwright study showed promise as a consummate match of community need and biomass use. There were problems but these are expected in any experimental, retro-fitted design.

Biomass-based cofiring installations may be desirable in areas with large local biomass supplies. One particular advantage is that cofiring installations are not as sensitive to economies of scale such as in the nuclear industry where it is infeasible to build "small" plants because of the investments in environmental studies, safety and security engineering.

Table 15 contains economic data and motivational reasons for cofiring in some actual situations.

Table 15, demonstrates considerable promise for cofiring wood wastes with coal and even oil. In fact, there is very little evidence of technical reasons against cofiring wood, and the economics look good for site-specific installations.

The following discussion covers some literature on the positive aspects of cofiring RDF fuel with coal in utility boilers.

Madison Gas and Electric Co. (MGE), Blount Station (BS), Madison, WI, has been burning RDF on a small but continuing scale since 1979.

Table 15. The Economics of Cofiring at Several Commercial Boiler Sites. Source [29].

Cofiring* Plant	Species Type	Purchase Basis	Fuel Cost ^a		Motivation
			bio.	other	
1	Hardwood wastes	Btu	coal .6	1.5	fav. economic comm. interest
2	Hardwood wastes	Btu	oil .6	5.0	fav. economic comm. interest
3	Softwood sawdust	wt.	coal 1.0	1.2	marg. economic
4	Softwood Aspen	wt.	coal .7	1.7	fav. economic comm. interest
5	Contaminated Seed Corn	N/A	N/A	N/A	fav. economic disposal prob.

*Plant 1: Northern States Power, Red Wing, Minnesota
 Plant 2: Northern States Power, French Island Wisconsin
 Plant 3: Grandhaven Board of Light and Power, Michigan
 Plant 4: Lake Superior District Power Co.
 Plant 5: Cedar Falls Utilities

^aCost figures are dollars per million Btu and not corrected for inflation.

BS burned 13,816 tons of RDF in 1984, and MGE declares that the performance of the fuel has been satisfactory [44]. BS has experienced no technical boiler problems not attributable to normal wear. In fact, stack emissions tests indicate that particulate emissions were not increased while cofiring and hydrochloric acid (HCL) emissions were no greater than they would be while burning a typical Midwest coal.

Despite the rosy technical picture, MGE has not been able to operate the BS plant for a profit. It should be mentioned that it continues operation because of support from the public sector.

Department of Electric and Water Utilities (DEWD), McIntosh Power Plant (MPP), City of Lakeland FL. Facility processes and burns an

average of 150 tons of raw MSW per day. The "processing" is a complete MSW-to-RDF plant. The MPP is the largest refuse-to-energy electric generating station in the U.S. [44]. The MSW-to-RDF processing facility is specifically designed to provide a supplemental fuel (10 percent) for the MPP boilers. It currently produces a revenue of \$30,000 per month.

For this plant the RDF has three to four times as much ash as the coal being burned, but since the unit was designed with this in mind there have been no problems. The boiler - Efficiency is reduced due to high moisture content (38 percent) and cold air introduced by the RDF pneumatic conveying system. However, it is noted that SO₂ emissions are down. Boiler Corrosion tests have shown that RDF burning could be doubled before significant corrosion occurs. Technically, the operation sounds efficient, however, it took two years to identify and correct the initial processing and burning problems. Despite this long "learning curve," the DEWD predicts the benefits, both environmental and economic, to be gained during the lifetime of the plant show solid waste disposal and power generation are profitable and compatible. The DEWD believes the benefits of reducing coal use and slowing landfill expansion should offset the cost of retro-fitting existing plants, or building new ones. This seems true if information such as that given in the DEWD report is made available, i.e. if we learn from others trials.

The preceding discussion indicates that cofiring woody or RDF biomass with coal (or oil) is technically feasible and economically beneficial in many circumstances. However, there are some technological problems that have been experienced while cofiring RDF in particular.

4.5.4 Negative Aspects

There are problems associated with both the quantity and quality of RDF ash. Extreme values of ash content range from 4.3 to 53.8

percent by dry weight [6]. Secondly, typical ash fusion temperatures are lower for RDF than coal in an oxidizing environment and nearly the same in a reducing environment [44]. This means that RDF ash has a greater potential to soften and stick to boiler surfaces and reduce heat transfer efficiency. "High" heat release boilers should be avoided for cofiring RDF [44]. Glass and aluminum can cause severe slagging problems if major quantities are not screened out.

There have been five material handling problems identified in the past. They are:

- 1) Dust along transport lines and in receiving stations.
- 2) RDF compaction and odors in storage bins due to long storage times.
- 3) Inconsistent RDF fuel reclaim flow due to bridging and corrosion.
- 4) Oversized materials, textiles, and wire plugging air lock feeder and/or transport lines.
- 5) Variation in RDF heat input to the boiler due to volumetric feed systems and inconsistent RDF heating value.

Detailed computer simulations have shown that a typical 200MW boiler will see a 1.9 to 4.2 percent decrease in efficiency at 20 percent RDF firing (heat input basis) [6]. There are two main reasons for this: 1) increased flue gas exit temperature, and 2) increased flue gas flowrate.

Increased flue gas flowrate is caused by higher excess combustion air necessary for proper firing of RDF. The reason for this is because of the high moisture content, and the higher reactivity of the cofired fuel, whether it is wood or RDF. The increased flowrate is also due to higher fuel mass flowrates to achieve the same Btu output as coal.

Increased flue gas exit temperature is due to the higher excess air requirements, and in many installations the preheat section (using exhaust gas) does not heat the RDF combustion air used for pneumatic

transport [11]. Decreased heat transfer due to slagging can also increase flue gas temperature.

The results of 1) and 2) above is to incur boiler losses due to dry gas heat loss, water vapor heat loss, and unburned combustibles (carried out by increased volumetric flowrates).

Steam generator manufacturers recommend maximum RDF cofiring rates of 20 percent of the total fuel heat input to insure HCl concentrations in the combustion gas are low enough to avoid increased corrosion on metal boiler surfaces [11]. The primary problem seems to be when bottom ash piles up onto water wall tubes, especially in tangentially fired units. Low oxygen levels and a reducing atmosphere next to the tubes catalyzes tube wastage due to RDF contact. Fortunately, no increased corrosion of superheater tube surfaces has been reported.

Currently, RDF cofiring plants have had little difficulty meeting Federal or State air quality standards. This may change rapidly however as there is current work on developing rigorous standards for a host of "new" pollutants including: acid gases (H_2SO_4 , HCl, SO_2 , HF, NH_3), heavy metal particulate, including (Pb, Zn, Cr, Sn,...), and trace organic compounds such as dioxin and furan [44].

5.0 EXPERIMENTAL COMBUSTION OF WOOD BIOMASS PELLETS

The Department of Mechanical Engineering at Oregon State University has built a Biomass Combustion Unit to burn pelletized biomass fuels. The BCU was designed to aid in the thermodynamic analysis of pellet fuel combustion and was used to analyze nine different pellet fuels under varying conditions of percent excess air (EA%), fuel flow-rate, and percent underfire air (UF%). The unabridged report on experimental combustion is found in reference [45].

5.1 Apparatus

Figures 17 and 18 show the BCU and a schematic of the associated equipment. Figure 17 shows the location of the under and overfire air tubes and shows the feed tube where wood biomass pellet fuel enters via a metering drum and horizontal auger. The fuel then drops by gravity onto the grate. The "cooling water feedtube" shown wrapped around the feed system, is there to prevent overheating of the auger system and to prevent pre-combustion of the pellets. Figure 17 also shows the port where combustion gases exit the BCU and continue to other test equipment and eventually are exhausted to the atmosphere.

To prevent damage to the stainless steel outer shell of the BCU and to promote thermal stability, the BCU is lined with three inches of high temperature ceramic refractory.

Figure 18 shows the major components of the system and are briefly described in the following. The combustion air is delivered by a compressor, flows through a desiccant + cotton - fiber filter and then into the "Air Dryer." The air is then metered to the underfire port, the overfire port and the cooling port for the "opacity monitor." The metering is by four rotometers or "Flowmeters". Once the UF and OF air is used for combustion and passes through the BCU, it goes to the "Opacity Monitor" where a measure of the exhausts opacity is made. Opacity, is the propensity for the exhaust to diminish light travel,

Figure 17. Cutaway View of the Biomass Combustion Unit (BCU). Shows Important Components Including: Overfire Air Tube, Underfire Air Port, Grate, Ceramic Refractory, Exhaust Port, and Pellet Fuel Feed Mechanism.

Figure 18. Schematic of the Entire Experimental Facility. Shows Flows of Inlet Air, Pellet Fuel and Exhaust Gases.

i.e. the greater the opacity the more "smokey" is the exhaust. It is measured on a scale from one to one hundred percent. Finally the spent combustion gases are drawn into the "Main Exhaust". However, during a portion of a test run the "Particulate Sampling Train" is used to draw a fraction of the exhaust gases through a glass fiber filter. This filter is later analyzed for the amount of particulate and the ratio of combustible to noncombustible components in the particulate (fly ash).

The triangular box to the right of the BCU in Fig. 18 is the "Fuel Hopper". Fuel is placed in the hopper and then transported by means of a motor driven metering drum down into the feed tube where a separate motor-driven horizontal auger pushes the fuel into the combustion chamber.

Above the BCU is the the X-Y gas and temperature probe table. The "X-Y Probe Table" consists of computer controlled stepper motors that turn screw shafts in both the horizontal and vertical directions.

Two (type-k) stainless steel clad thermocouple probes and a gas analysis probe were used in the experiment. The gas analysis probe is the sampling end of a combustion gas analysis unit which measures the following parameters:

- 1) Carbon dioxide;
- 2) Oxygen;
- 3) Carbon monoxide;
- 4) Oxides of nitrogen;
- 5) Sulfur dioxide;
- 6) Combustible hydrocarbons; and
- 7) "Real-time" for each sample that was "data-logged".

Other sensors provided additional information when needed. They included, pressure gages, particulate sampling train, and more type-k thermocouples. Shown schematically in Figure 18 is the "Control Unit". The heart of this system is a microcomputer. This computer and some

associated data acquisition hardware was used to gather temperature and gas composition data from the probes. It also gathered temperature data from a number of other locations in the system and gives the commands that move the stepper motors.

To aid the investigation, a Quick-Basic program was written that combined all functions. This meant that most of the data acquisition was automatic and required no additional work besides setting the initial program parameters such as length of run and sampling rate and starting the program. Specifically, the only data reported in this experimental investigation that was not "data-logged" by the Control Unit was the data from the "Particulate Sampling Train" and fuel flowrate.

5.2 Experiments

The Biomass Combustion Unit (BCU) facility was used to perform the three following experiments:

- 1) Determine the optimal EA% and UF% for one fuel. Optimal refers to the most thermodynamically complete combustion, i.e. combustion that is 100 percent efficient by the First Law of Thermodynamics.
- 2) Test the characteristics and efficiency of multiple fuels over a range of feed rates and excess air (EA%) holding UF% constant.
- 3) Test multiple fuels for the effect of increasing the underfire air temperature to approximately 300°F.

These experiments were performed while fixing many variables constant and attempting to operate in a "steady-state" manner. Steady-state implies that no changes in inlet air or fuel mass flows or properties occurred and the combustion proceeded with unchanged characteristics in time. The underfire air and overfire flowrates and temperatures, the pressure in the BCU, and the fuel mass flowrate were held constant for all test runs.

The temperature and gas analysis probes were positioned 20 inches above the grate for all experiments and the overfire air tube was placed 4 inches above the grate. Test runs were for either 1 or 1-1/2 hour duration with 30 data points taken equally spaced in time for all relevant variables.

5.2.1 Optimal Firing Conditions

This experiment was performed to determine the "optimal" percentages of underfire air (UF%) and excess air (EA%) for one pellet specie. "Optimal" for this set of experiments is when the combustion gases are highest in measured carbon dioxide (CO_2). When CO_2 is a maximum, the available carbon in the fuel is being burned most completely (produces the greatest liberation of heat). Hydrogen (H_2), is the other main combustible constituent in the wood pellets, but combustion tests indicate very little combustible hydrocarbons in the measured exhaust which indicates that "most" H_2 is burned to water vapor before reaching the gas analysis probe. Other gas properties were analyzed in a more qualitative sense to help support the findings based on measured CO_2 percent. Table 16, gives these variables.

Tests were performed with excess air level chosen and then the five UF% air levels were randomly chosen in time. The experimental matrix was designed for EA% values of 30 percent, 40 percent and 50 percent; however, the final value varied because of the slightly variable nature of the fuel feed system. For each block, 30 data points were collected over one hour.

Test Results

Figure 19 is a plot of six scaled gas parameters versus UF% at a specified level of EA%. The "scaled" variables are the actual values divided by the largest value in a column, i.e. all CO_2 values in a column were divided by the maximum CO_2 value in that column. This

Table 16. Gas Property Values at Optimal Firing.

Expected Value at Optimal	
Variable	Firing Condition
Temperature	Maximum
Carbon Monoxide	Minimum
Oxides of Nitrogen	Maximum
Particulate (fly ash)	Minimum
Combustible (% in fly ash)	Minimum

Figure 19. Gas Parameters for Pellet (1) Scaled by the Largest Value in the Test Column. The Gas Parameters are Plotted as a Function of UF% at a Level of 41.0% Excess Air (41.0 EA%).

yields plots with all the dependent variables scaled from zero to one which makes qualitative analysis of trends easy.

At 30 percent underfire air, Figure 19 shows that Temperature, CO₂, and NO_x are at maximums, Particulate is near minimum, CO and combustibles are at true minimums. This corresponds well to the predicted optimal solution shown in Table 16. At an excess air level of 41.0 percent and 30 percent underfire air the combustion of this pellet fuel was optimal.

Plots like Figure 19 were produced for tests at other excess air levels. The trends in scaled gas parameters were very similar. They showed an optimal UF% of nearly 30 percent. One major difference occurred at the excess air level of 87 percent and higher. At this level all curves were "flat" and located close to each other. It is hypothesized that this effect is due to the fact that at very high excess air levels the fuel bed experiences turbulence and there is no distinguishable "over" or "under" fire air. This hypothesis is supported by visual observation. It was observed that only a very thin fuel bed existed at this EA% level, while at the other two lower levels there were well developed fuel beds.

A new variable is defined as the CO₂-based efficiency (CO₂EFF). It is the measured percentage of CO₂ in the combustion gases divided by the percentage of CO₂ calculated for the complete ("theoretical" or "stoichiometric") combustion of the available fuel. CO₂EFF is defined as

$$\text{CO}_2\text{EFF} = (\text{CO}_{2\text{measured}} / \text{CO}_{2\text{theoretical}}) \times 100 \quad (16)$$

It is assumed that the combustion energy losses due to CO production, combustibles in fly ash, and hydrocarbons, is negligible. This is supported by the data for these three loss mechanisms which shows that their percentages or measure in parts per million (ppm) is very small.

Figure 20 shows the constant EA% curves for CO₂EFF versus UF%. The plots for excess air values of 41.0 percent and 87.23 percent have the same shape. They run parallel but at different "levels" of EA%. Their efficiencies range between 70 and 95 percent. The curve at 20.8 percent excess air shows a marked average drop in efficiency. This is due to oxygen "starvation" of the combusting fuel bed. The final conclusion is that the optimal operating point is at 30 percent underfire air and 41.0 percent excess air.

Figure 21, shows a plot of the surface of the curve which represents the numerical approximation for the relationship of CO₂EFF as a function of EA% and UF%. A six-parameter, second-order polynomial was "fit" by the method of least-squares to the 15 mean CO₂-based efficiency data points from experiment number 1.

For this model, $R^2 = 85.68$ percent is an indicator of a fairly strong association between the two independent variables (EA% and UF%) and the dependent variable (CO₂EFF). Unfortunately, because there is only one observation at each point there is no error term or variance for this model. It is assumed that the qualitative evidence using Figures 19 and 20 help support the model's validity.

Next, the equation that describes the surface in Figure 21 was differentiated with respect to the two independent variables and the subsequent equations were set equal to zero and solved simultaneously. The solution was a stationary point for the CO₂EFF surface and a maximum by visual observance of Figure 21. The calculated optimal firing condition was found to be CO₂EFF = 96.2 percent at EA% = 59.5, and UF% = 35.46. This corresponds fairly well with the optimal point found by graphical analysis of the raw data (Figures 19 and 20) which gave a solution of EA% = 41.0 and UF% = 30.0.

Figure 20. Level Curves of CO₂-Based Efficiency as a Function of Under Fire Air Percent at Different Excess Air Percents.

Figure 21. CO₂-Based Efficiency Surface as a Function of Excess Air Percent and Underfire Air Percent. This Represents a Numerical Approximation of the "True" Functional Relationship and Uses 15 Discrete Data Points to Fit the Model.

5.2.2 Multiple Fuels Comparison

This experiment was performed to investigate how different wood fuel pellets would perform during combustion with identical input values of fuel feed rate (FFR), excess air percent (EA%), and underfire air percent (UF%). Originally it was planned to perform the tests at "exactly" the same feed rate (mass basis), and levels of excess and underfire air percents. However, due to the fuel feed variability it was not possible to hold FFR or EA% constant. Fortunately the UF% was held constant at 30 percent, and the variability in FFR and EA% was only 10.2 and 27.4 percent respectively.

Each test was for one half hour with 30 equally spaced gas analysis data points taken. The order of fuel pellet firing was randomized to negate any time series effects. As mentioned above the FFR and EA% levels were preset to be the same for all tests but there was slight variability between tests. The FFR and EA% during any one test was controlled very precisely. This variability in FFR is attributable to the difference in feed characteristics between fuels, however, no attempt was made to correlate whether this was due to dimensional, density, or other related pellet physical variables.

The easiest way to compare the performance of each fuel was to tabulate minimum (MIN), maximum (MAX), mean, and percent standard deviation (%SDEV) data in tabular form. Table 17, shows the fuel code and associated test number along with the input parameters of FFR and EA%. Note that UF% was held constant at 30.0. These data show that the FFR varied by only 10.2 percent whereas the EA% varied by 27.4 percent. It is also true that the range of EA% is within the "starved" or low EA% level (20.8 percent) and "turbulent" or high EA% level as found in the optimal firing experiment.

Table 18 contains various combustion gas data for this experiment. The table shows that the gas temperature only varied by 5.2 percent and similarly the CO₂-based efficiency varied by only 5.4 percent. This

Table 17. Fixed Parameters and Coding for Experiment #2.

Code	FFR (Btu/hr)	EA% (%)
1	42246.5	41.0
5	42158.4	29.2
2	35208.1	50.4
6	40735.1	33.1
7	33798.3	52.4
4	40469.6	28.7
3	34912.2	52.3
8	37437.8	47.0
9	31019.2	68.2
	MIN: 31019.2	29.2
	MAX: 42246.5	68.2
	MEAN: 37553.9	44.7
	%SDEV ^a : 10.2	27.4

^a%SDEV = (standard deviation/mean) x 100. This is used because it is a more meaningful measure of the variance for comparing different variables.

Table 18. Combustion Gas Data for Experiment #2.

	Gas			Particulate Combustible		
	Temp. (°F)	CO ₂ EFF (%)	CO (ppm)	NO _x (ppm)	(fly ash) (grs./dscf)	(fly ash) (%)
MIN	1337.5	75.9	4.1	79.4	.029	.98
MAX	1576.8	92.2	188.2	215.0	.705	89.6
MEAN	1420.1	82.1	125.7	154.4	.204	16.3
%SDEV	5.2	5.4	41.6	27.2	123.3	166.8

indicates that despite the difference in ash content, moisture content, elemental, proximate, and ash fusion analyses, these fuels burn with very similar properties under similar input conditions. The carbon monoxide levels show a 41.6 percent deviation, but that is reduced to 33 percent if the far outlier (4.1 percent CO) is not considered.

The particulate (fly ash) data are highly skewed by pellets coded (4), (8), and (9), which had values of particulate in the tenth's range while all other pellets had values in the hundredth's. Opacity was measured for all experiments but was not reported because it was zero for all runs except the tests which correspond and to pellet (8) which has the highest salt content. The salt content is determined by the percent chlorine by ultimate analysis. This result is reasonable because pellets (8) and (9) had the highest ash and chlorine contents of all pellets. Pellet (8) had ash = 2.55 percent, Cl = .78 percent and pellet (9) had ash = 2.43 percent, Cl = .19 percent. Pellet (4) had a moderately high ash content of .96 percent and no chlorine, but its specie is Hemlock Fir which is noted in the forest products industry for burning with high opacity and particulate.

The NO_x data ranges from 79.4 to 215.0 parts per million with %SDEV equal to 27.2. The data on particulate and combustibles in fly ash has the largest spread. This may be due to the fact that these quantities were sampled for only 15 minutes for each test, and had a greater margin for human error than the "data-logged" variables.

It was mentioned in the optimal firing experiment that fuel feed rate has little effect on the CO₂-based combustion efficiency (CO₂EFF), at least over the ranges experienced during these tests. To support this hypothesis the data in the multiple fuels experiment were examined.

Figure 22 shows CO₂EFF as a function of FFR (Btu/hr). A linear regression showed the slope (b1) to be very small (b1 = 4.87E-4). The slope represents the unit change in CO₂EFF expected for a unit change in FFR. Statistical analysis show that there is no relationship

Figure 22. Plot and Linear Regression Line for Carbon Dioxide Based Efficiency (CO2EFF) versus Fuel Feed Rate (FFR) for Experiment #2.

between FFR and CO2EFF. This assumes that the linear model is appropriate and by observation of the data that appears as the best choice.

The most striking observation made was that after the tests with the salty pellets there was visible ash in the grate after "cool-down". For all prior tests, no matter how long the test sequence, there was never any visibly remaining ash aside from a "few specks". There was also fine crystalline matter deposited on metal surfaces in the BCU combustion chamber. These surfaces were the gas analysis probes at mid to upper height and the cooling water feed tube. Both of these surfaces were relatively "cool" compared to the rest of the chamber and thus acted as condensing surfaces. Most dramatically, there was evidence of corrosion (pitting of stainless steel surfaces) after less than one hour of burning these fuels that were high in ash and salt content.

5.2.3 Effect of Preheated Combustion Air

This experiment was performed to investigate the effect of increased underfire air temperature on combustion efficiency. Tests ("hot-tests") were completed on five pellet species coded (1), (2), (4), (8), and (9). The results of a hot test were compared to the previous results of a "cold-test" on the same pellet.

Similar to Experiments #1 and #2, there was undesired variability in the fuel feed rate. The original experimental plan was to have each pellet fed to the Biomass Combustion Unit at the same rate (mass basis) as the respective cold-test. The mean difference of cold-test minus hot-test fuel feed rate was -6611.4 (Btu/hr), or a decrease of 16.1 percent from the mean hot-test feed rate. The following analysis assumes that the fuel feed rate variability is inconsequential compared to the effect of the heated underfire air.

Test methods were identical to the multiple fuel experiment except that the underfire air temperature was increased to a mean of 306.4°F. This represents a mean temperature rise of 230°F above the cold-test temperature, with a standard deviation of only .18 percent.

The five pellet samples were chosen randomly except for pellets (8) and (9). These pellets were chosen because they were the worst fuels in terms of ash and corrosion problems as observed in and it was desired to observe them under other operating conditions. The test was randomized to reduce time series effects.

Table 19 shows the results of the hot underfire air tests versus the cold underfire air tests. "GTEMP" is the combustion gas temperature and CO2EFF is the CO₂-based efficiency as for the previous experiments.

Table 19. Combustion Gas Temperature and CO₂-based Efficiency Data for Cold and Hot Underfire Air Tests.

Pellet Code	COLD-TEST		HOT-TEST	
	GTEMP (°F)	CO2EFF (%)	GTEMP (°F)	CO2EFF (%)
(1)	1247.63	96.37	1280.43	93.04
(2)	1354.29	84.67	1485.24	74.66
(4)	1482.34	80.80	1469.99	88.73
(8)	1448.46	81.46	1598.78	95.98
(9)	1348.10	79.24	1483.39	103.90 ^a
MEAN	1409.60	85.79	1457.00	91.26
SDEV	106.33	6.34	128.1	9.67

^aTheoretically, this value cannot be greater than 100 percent but this more extreme value (103.90) is due to random experimental error. The combustion can be considered to be *nearly* 100 percent efficient based on measured CO₂.

The graphical evidence in Figure 23 appears to show that the hot-tests increase efficiency by a significant margin. The increase however cannot be substantiated by statistical analysis without further testing. There is a significant increase in the exit temperature.

Increasing the underfire air temperature by 230°F on average did not increase the combustion efficiency (CO2EFF) by a statistically significant amount (95 percent confidence level). Increasing the underfire air temperature did however increase the combustion gas temperature by 87.4°F. The average exit temperature for the preheat incoming air only 6.2 percent larger than the mean cold-test exit gas temperature. Many hogged-fuel boilers operate with preheated air. These test results indicate that preheated air is utilized in fuel drying rather than driving combustion further to completion. Some furnaces require as much as 200 percent excess (preheated) air. They find that this is necessary to sustain combustion of "wet" fuel.

Figure 23. Carbon Dioxide Based Efficiency (CO2EFF) versus Fuel Code, for Cold and Hot Tests.

The particulate (fly ash), combustible (in fly ash), NO_x , and other data were not analyzed since they did not present significant variability from the cold to hot tests. For more detailed information on the previous three experiments and the wood pellet fuels see reference [45].

5.3 Conclusions

Results show that two very important measures of combustion efficiency (gas temperature and carbon dioxide based efficiency) varied by only 5.2 and 5.4 percent respectively. This indicates that all nine different wood fuel pellet types behave very similarly under the prescribed range of operating parameters. The overall mean efficiency for all tests was 82.1 percent and the overall mean temperature was 1420.1°F.

Particulate (fly ash) and combustible (in fly ash) data showed the greatest variability. There was evidence of a relationship between maximum values for both particulate and combustible and the percentages of ash and chlorine in the pellet fuel. The greater the percentage of ash and chlorine (salt), the greater was the fly ash problem, also, combustion efficiency was decreased by combustible losses (unburned hydrocarbons) in the fly ash.

Carbon monoxide and Oxides of Nitrogen showed the next greatest variability, but neither had data values greater than 215.0 parts per million (215.0 ppm is a very small quantity, i.e. 1 ppm = .001 grams/liter = $6.2E-5$ lbm/ft³).

Visual evidence indicates that pellet fuels produced from salt laden material are corrosive, produce the largest quantities of ash, and form the only slag or clinker formations of all nine fuels. The corrosion is directly attributable to salt content (or more specifically, chloride ions and compounds formed during combustion).

BIBLIOGRAPHY

1. Gershman, et al., *Small Scale Municipal Solid Waste Energy Systems*, Van Nostrand Reinhold, New York, 1986.
2. Sonntag, R.E. and Van Wylen, G., "Chemical Reactions," *Introduction to Thermodynamics, Classical and Statistical*, 2nd. ed., John Wiley and Sons, New York, 1982, pp. 449-500.
3. Junge, D.C., "Boilers Fired with Wood and Bark Residue," *Research Bulletin 17*, Forest Research Laboratory, Oregon State Univ., Corvallis, OR, 1975.
4. Vaughan, D.A., Krause, H.H. and Boyd, W.K., "Chloride Corrosion and its Inhibition in Refuse Firing," *Proceedings of the International Conference on Ash Deposits and Corrosion from Impurities in Combustion Gases*, New England College, Henniker, NH, American Society of Mechanical Engineers, June 26-July 1, 1977, pp. 473-493.
5. Domalski, E.S., Jobe, T.L. Jr., and Milne, T.A., "Thermodynamic Data for Biomass Conversion and Waste Incineration," *Report No. SERI/SP-271-2839*, Solar Energy Research Institute, Golden, CO, Sept. 1986.
6. *Guidelines for Cofiring Refuse-Derived Fuel in Electric Utility Boilers (Volume 3: Appendices)*, CS-5754, Vol. 3, Research Project 1861-1, Electric Power Research Institute, Palo Alto, CA, June 1988.
7. Singer, J.G., ed., *Combustion, Fossil Power Systems*, 3rd ed., Combustion Engineering, Inc., Windsor, CT, 1981.
8. Wilson, P.L., Funck, J.W., and Avery, R.B., "Fuelwood Characteristics of Northwestern Conifers and Hardwoods," *Research Bulletin 60*, Forest Research Laboratory, College of Forestry, Oregon State University, Sept. 1987.
9. Browne, F.L., "Theories of the Combustion of Wood and its Control," *Report 2136*, USDA Forest Products Laboratory, Madison, WI, Dec. 1958.
10. Dadkhah-Nikoo, A., "Analysis of Wood Combustion and Combustion Systems for a Combined Cycle Wood-Fired Power Plant," *Masters Thesis*, Dept. of Mechanical Engineering, Oregon State Univ., Aug. 1985.
11. *Guidelines for Cofiring Refuse-Derived Fuel in Electric Utility Boilers (Volume 1: Executive Summary)*, CS-5754, Vol. 1, Research Project 1861-1, Electric Power Research Institute, Palo Alto, CA, June 1988.

12. Sampson, G.R., Richmond, A.P., Brewster, G.A., and Gasbarro, A.F., "Potential for Co-firing Wood Chips with Coal in Interior Alaska," Bonneville Power Administration Report No. DE-AI79-84BP17610, Pacific Northwest Research Station (USDA Forest Service), Portland OR, July 1987.
13. Simmons, W.W. and Ragland K.W., "Burning Rate of Millimeter Sized Wood Particles in a Furnace," *Combustion Science and Technology*, Vol. 46, 1986, pp. 1-15.
14. Smith, W.R., "Wood Fuel Preparation," *Progress in Biomass Conversion*, Vol. 2, Academic Press, Inc., 1980, pp. 181-211.
15. Dadkhah-Nikoo, A. and Bushnell, D.J., "Analysis of Wood Combustion Based on the First and Second Laws of Thermodynamics," *Journal of Energy Resources Technology*, Vol. 109, Sept. 1987, pp.129-141.
16. *Pacific Northwest and Alaska Bioenergy Program Glossary*, U.S. Department of Energy, Bonneville Power Administration, Portland OR, March 1986.
17. Levie, B., Diebold, P., and West, R., "Pyrolysis and Combustion of Refuse Derived Fuel," Solar Energy Research Institute, Golden, CO, 1988.
18. Levi, M.P. and O'Grady, M.J., "Decisionmaker's Guide to Wood Fuel for Small Industrial Energy Users," Department of Energy, Contract No. EG-77-C-01-4042, Solar Energy Research Institute, Golden, CO, Feb. 1980.
19. Martin, W. and Koenigshofer, D.R., "Development and Testing of a Small Wood Combustion System," *Fuels from Biomass and Wastes*, Eds. Klass D.L. and Emert, G.H., pp. 567-581.
20. Stafford, J.L., "Drying Bagasse Using Boiler Flue Gas," Conference: Hawaiian Sugar Technologists Conference, Honolulu, Hawaii, Nov. 1975.
21. Westphal, J.A., "Dehydration, Heat Recovery and Densification of Fuel for Direct Combustion," Presented to: North American Sawmill and Panel Clinic Wood Energy Workshop, Portland OR, March 1980.
22. Tillman, D.A. and Anderson, L.L., "Computer Modelling of Wood Combustion with Emphasis on Adiabatic Flame Temperature," *Journal of Applied Polymer Science: Applied Polymer Symposium 37*, John Wiley and Sons, 1983, pp. 761-775.
23. Huff, E.R., "Effect of Size, Shape, Density, Moisture, and Furnace Wall Temperature on Burning Times of Wood Pieces," *Fundamentals of Thermochemical Biomass Conversion*, Elsevier Applied Science Publishers, New York, NY, 1982, pp. 761-766.

24. Kanury, A.M., "Mass Regression in the Pyrolysis of Pine Wood Macrocyllinders in a Nitrogen Atmosphere - An Experimental Study," *Combustion Science and Technology*, Vol. 9, 1974, pp. 31-36.
25. Kanury, A.M., "Thermal Decomposition Kinetics of Wood Pyrolysis," *Combustion and Flame*, Vol. 18, 1972, pp. 75-83.
26. Simmons, W.W. and Ragland K.W., "Single Particle Combustion Analysis of Wood," *Fundamentals of Thermo-Chemical Biomass Conversion*, Elsevier Applied Science Publishers, New York, 1982, pp. 777-792.
27. *Standard for Densified Wood Pellet Fuel for Residential Use*, Standard No. APFI-PF-1-88, Association of Pellet Fuel Industries, Sparks, NV, May 1988.
28. *Fiber Fuels Institute*, "Biomass Fuels Standard Specifications Development Final Report," Duluth, MN, 1988, Department of Energy, Contract No. DE-FG05-83OR21390.
29. *Evaluation of Biomass Systems for Electricity Generation*, Report No. EPRI AP-2265, Project 1348-7, Electric Power Research Institute, Palo Alto, CA, Feb. 1982.
30. Kanury, A.M., "Rate of Burning of Wood," *Combustion Science and Technology*, Vol. 5, 1972, pp. 135-146.
31. Kerekes, Z.E., Bryers, R.W., and Sauer, A.R., "The Influence of Heavy Metals Pb and Zn on Corrosion and Deposits in Refuse-Fired Steam Generators," *Proceedings of the International Conference on Ash Deposits and Corrosion from Impurities in Combustion Gases*, New England College, Henniker, NH, American Society of Mechanical Engineers, June 26-July 1, 1977, pp. 455-471.
32. "Energy from Waste: On-Site Heat-Recovery Incineration," *Power*, March 1987.
33. Sengupta, S. and Wong, K.-F. V., eds., *Resource Recovery from Solid Wastes*, (Proceedings of a conference held in Miami Beach, FL, May 10-12, 1982), Pergamon Press, New York, 1982.
34. Wolpin, B., "Pellets Promise Profits for Minnesota RDF Plant," *World Wastes*, January 1988.
35. Tuttle, K.L., "Combustion Mechanisms in Wood Fired Boilers," *Ph.D Thesis*, Dept. of Mechanical Engineering, Oregon State Univ., Corvallis, OR, June 1978.
36. *Bench-Scale Combustion Characterization of Cleaned Kentucky No. 9 Coals*, Report No. CS-5070, Research Project 2425-4, Electric Power Research Institute, Palo Alto, CA, Feb. 1987.

37. Shafizadeh, F., *Fuels from Wood Waste*, Anderson, L.L. and Tillman, D.A., Eds., Academic Press, Inc., 1977.
38. DeAngelis, D.G., Ruffin, D.S., Peters, J.A., and Reznick, R.B., "Source Assessment: Residential Combustion of Wood," *Report No. 68-02-1874*, Task No. 23, Environmental Protection Agency, EPA-600/2-80-0426, March 1980.
39. Junge, D.J., "The Combustion Characteristics of Pelletized Douglas Fir Bark," *Report No. 12*, U.S. Department of Energy, Contract No. EY-76-C-06-2227, Task Agreement No. 22, Sept. 1979.
40. Glassman, I., "Environmental Combustion Considerations," *Combustion*, 2nd ed., Academic Press, Inc., Orlando, FL, 1987, pp. 318-385.
41. *Technology Assessment: Municipal Solid Waste as a Utility Fuel*, Report No. EPRI CS-2409, Project 1255-3, Electric Power Research Institute, Palo Alto, CA, May 1982.
42. Atili, B., Cueto, H., and Daugherty, K., "Determining Acid Gases, Trace Metals, and Organics from Cofiring Blends of Coal and Densified Refuse-Derived Fuel (dRDF)," Draft Document submitted to Argonne National Laboratory, by North Texas State University, Contract No. 33071401, October 31, 1987.
43. Hickman, H.L. Jr., Turner, W.D., Hopper, R., et al., *Thermal Conversion Systems for Municipal Solid Waste*, Park Ridge, NJ, Noyes, 1984.
44. "Municipal Solid Waste as a Utility Fuel," *Proceedings*, Madison, WI, Nov. 1986, Report No. CS-4900-SR, Electric Power Research Institute, Palo Alto, CA.
45. Haluzak, C., "Experimental Combustion Analysis and Development of Representative Fuel Specifications for Selected Wood and Refuse Derived Fuel Pellets from the Pacific Northwest," Ph.D. Thesis, Department of Mechanical Engineering, Oregon State University, May 1989.

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APPENDIX A

Pellet Codes

Pellet Sample Coding Used in this Report
and for Other Work Performed at OSU.

OSU Code Name	Report Code
BCCPP824-1AB*	1
FHLDF624-1AB	2
FHLDF624-2AB	3
PHCHF706-2AB	4
EVCMX713-1AB	5
WSPCD715-1AB	6
KMPMX727-2AB	7
SPCDF727-1AB	8
WFPMX920-1AB	9
PHCMX706-1	10
HSIMX824-1	11
BTPMX920-1	12
WDMMX920-1	13
RMMMX920-1	14

*A => Pellets were analyzed for Proximate and Ultimate Analysis.

B => Pellets were burned for the experimental data analyzed in this report.

If an "A" or "B" is not present, this means that the pellets were analyzed for a subset of the variables included in this report excluding ultimate and proximate analysis and experimental burning.

APPENDIX B

Pellet Fuel Data

ALL INFORMATION CONTAINED
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PELLET SAMPLE DATA

Pellet Code: 1

Pellet Species = Ponderosa Pine (wood only)
Location of Raw Material = Lower "Pan Handle" Idaho
Grade = Commercial Pellet

Ultimate analysis (dry weight basis)

% Carbon	= 51.20	% Hydrogen	= 6.35
% Oxygen	= 41.97	% Nitrogen	= .25
% Sulphur	= .01	% Chlorine	= .01
% Ash	= .22		

Proximate Analysis (dry weight basis)

% Fixed Carbon = 16.63 % Volatile = 83.15
% Ash = same as in ultimate analysis

Ash Fusion Data

Initial = 2450.00 (°F)
H/W = 2470.00 (°F)
1/2-H/W = 2480.00 (°F)
Fluid = 2510.00 (°F)

Additional Pellet Fuel Parameters

Rapeseed Supplement (% wet basis)^a = 0.00
Higher Heating Value = 8967.63 (Btu/lbm)
Moisture Content (% wet basis) = 8.25
Bulk Density = 38.63 (lbm/ft³)
Specific Density = 81.28 (lbm/ft³)
Mean Length = .266 (inches)
Mean Diameter = .323 (inches)

^aRapeseed was added in small percentages to some hogged biomass that was collected by OSU to be made into pellets. The rapeseed aids in pellet manufacture.

PELLET SAMPLE DATA

Pellet Code: 2

Pellet Species = Douglas Fir (wood + bark)
Location of Raw Material = Central Western Oregon
Grade = Non-Commercial (made for OSU)

Ultimate Analysis (dry weight basis)

% Carbon	= 50.82	% Hydrogen	= 6.35
% Oxygen	= 42.54	% Nitrogen	= .06
% Sulphur	= .02	% Chlorine	= 0.00
% Ash	= .21		

Proximate Analysis (dry weight basis)

% Fixed Carbon	= 15.66	% Volatile	= 84.13
% Ash	= same as in ultimate analysis		

Ash Fusion Data

Initial = 2510.00 (°F)
H/W = unav. (°F)
1/2-H/W = unav. (°F)
Fluid = 2540.00 (°F)

Additional Pellet Fuel Parameters

Rapeseed Supplement (% wet basis) ^a	= 1.00
Higher Heating Value	= 8928.29 (Btu/lbm)
Moisture Content (% wet basis)	= 11.20
Bulk Density	= 45.50 (lbm/ft ³)
Specific Density	= 80.64 (lbm/ft ³)
Mean Length	= .701 (inches)
Mean Diameter	= .312 (inches)

^aRapeseed was added in small percentages to some hogged biomass that was collected by OSU to be made into pellets. The rapeseed aids in pellet manufacture.

PELLET SAMPLE DATA

Pellet Code: 3

Pellet Species = Douglas Fir (wood + bark)
Location of Raw Material = Central Western Oregon
Grade = Non-Commercial (made for OSU)

Ultimate Analysis (dry weight basis)

% Carbon	= 53.29	% Hydrogen	= 6.16
% Oxygen	= 39.42	% Nitrogen	= .13
% Sulphur	= .01	% Chlorine	= 0.00
% Ash	= .99		

Proximate Analysis (dry weight basis)

% Fixed Carbon	= 20.88	% Volatile	= 78.13
% Ash	= same as in ultimate analysis		

Ash Fusion Data

Initial = 2210.00 (°F)
H/W = unav. (°F)
1/2-H/W = unav. (°F)
Fluid = 2250.00 (°F)

Additional Pellet Fuel Parameters

Rapeseed Supplement (% wet basis) ^a	= 2.00
Higher Heating Value	= 8970.01 (Btu/lbm)
Moisture Content (% wet basis)	= 11.20
Bulk Density	= 45.50 (lbm/ft ³)
Specific Density	= 80.64 (lbm/ft ³)
Mean Length	= .701 (inches)
Mean Diameter	= .312 (inches)

^aRapeseed was added in small percentages to some hogged biomass that was collected by OSU to be made into pellets. The rapeseed aids in pellet manufacture.

PELLET SAMPLE DATA

Pellet Code: 4

Pellet Species = Hemlock Fir (wood + bark)
Location of Raw Material = Central Western Oregon
Grade = Non-Commercial (made for OSU)

Ultimate Analysis (dry weight basis)

% Carbon	= 51.16	% Hydrogen	= 6.09
% Oxygen	= 41.68	% Nitrogen	= .10
% Sulphur	= .01	% Chlorine	= 0.003
% Ash	= .96		

Proximate Analysis (dry weight basis)

% Fixed Carbon	= 21.06	% Volatile	= 77.98
% Ash	= same as in ultimate analysis		

Ash Fusion Data

Initial	= 2500.00 (°F)
H/W	= 2530.00 (°F)
1/2-H/W	= 2540.00 (°F)
Fluid	= 2550.00 (°F)

Additional Pellet Fuel Parameters

Rapeseed Supplement (% wet basis) ^a	= 0.00
Higher Heating Value	= 8786.94 (Btu/lbm)
Moisture Content (% wet basis)	= 8.40
Bulk Density	= 48.16 (lbm/ft ³)
Specific Density	= 83.92 (lbm/ft ³)
Mean Length	= .518 (inches)
Mean Diameter	= .310 (inches)

^aRapeseed was added in small percentages to some hogged biomass that was collected by OSU to be made into pellets. The rapeseed aids in pellet manufacture.

PELLET SAMPLE DATA

Pellet Code: 5

Pellet Species = Alder, Hemlock Fir, Douglas Fir, Cedar
(wood+bark)
Location of Raw Material = Central Coast Oregon
Grade = Non-Commercial (made for OSU)

Ultimate Analysis (dry weight basis)

% Carbon	= 53.41	% Hydrogen	= 6.05
% Oxygen	= 37.99	% Nitrogen	= .27
% Sulphur	= .03	% Chlorine	= 0.00
% Ash	= 2.24		

Proximate Analysis (dry weight basis)

% Fixed Carbon	= 23.78	% Volatile	= 73.98
% Ash	= same as in ultimate analysis		

Ash Fusion Data

Initial	= 2260.00 (°F)
H/W	= 2270.00 (°F)
1/2-H/W	= 2275.00 (°F)
Fluid	= 2280.00 (°F)

Additional Pellet Fuel Parameters

Rapeseed Supplement (% wet basis) ^a	= 0.25
Higher Heating Value	= 9185.71 (Btu/lbm)
Moisture Content (% wet basis)	= 3.40
Bulk Density	= 44.47 (lbm/ft ³)
Specific Density	= 81.57 (lbm/ft ³)
Mean Length	= .317 (inches)
Mean Diameter	= .315 (inches)

^aRapeseed was added in small percentages to some hogged biomass that was collected by OSU to be made into pellets. The rapeseed aids in pellet manufacture.

PELLET SAMPLE DATA

Pellet Code: 6

Pellet Species = Cedar (wood + bark)
Location of Raw Material = South Central Oregon
Grade = Non-Commercial (made for OSU)

Ultimate Analysis (dry weight basis)

% Carbon	= 52.10	% Hydrogen	= 6.15
% Oxygen	= 41.03	% Nitrogen	= .01
% Sulphur	= .01	% Chlorine	= 0.00
% Ash	= .61		

Proximate Analysis (dry weight basis)

% Fixed Carbon	= 18.69	% Volatile	= 80.70
% Ash	= same as in ultimate analysis		

Ash Fusion Data

Initial	= 2220.00 (°F)
H/W	= 2230.00 (°F)
1/2-H/W	= 2240.00 (°F)
Fluid	= 2250.00 (°F)

Additional Pellet Fuel Parameters

Rapeseed Supplement (% wet basis) ^a	= 0.25
Higher Heating Value	= 9141.63 (Btu/lbm)
Moisture Content (% wet basis)	= 7.80
Bulk Density	= 48.95 (lbm/ft ³)
Specific Density	= 82.38 (lbm/ft ³)
Mean Length	= .46 (inches)
Mean Diameter	= .307 (inches)

^aRapeseed was added in small percentages to some hogged biomass that was collected by OSU to be made into pellets. The rapeseed aids in pellet manufacture.

PELLET SAMPLE DATA

Pellet Code: 7

Pellet Species = Red Alder, some Maple/Myrtle
(wood + bark)
Location of Raw Material = Central Coast Oregon
Grade = Non-Commercial (made for OSU)

Ultimate Analysis (dry weight basis)

% Carbon	= 50.35	% Hydrogen	= 5.92
% Oxygen	= 42.29	% Nitrogen	= .27
% Sulphur	= .03	% Chlorine	= 0.00
% Ash	= 1.15		

Proximate Analysis (dry weight basis)

% Fixed Carbon	= 19.25	% Volatile	= 79.60
% Ash	= same as in ultimate analysis		

Ash Fusion Data

Initial	= 2220.00 (°F)
H/W	= 2220.00 (°F)
1/2-H/W	= 2230.00 (°F)
Fluid	= 2240.00 (°F)

Additional Pellet Fuel Parameters

Rapeseed Supplement (% wet basis) ^a	= 0.50
Higher Heating Value	= 8688.26 (Btu/lbm)
Moisture Content (% wet basis)	= 6.60
Bulk Density	= 53.34 (lbm/ft ³)
Specific Density	= 82.86 (lbm/ft ³)
Mean Length	= .705 (inches)
Mean Diameter	= .305 (inches)

^aRapeseed was added in small percentages to some hogged biomass that was collected by OSU to be made into pellets. The rapeseed aids in pellet manufacture.

PELLET SAMPLE DATA

Pellet Code: 8

Pellet Species = Douglas Fir (wood + bark)
Location of Raw Material = Central Coast Oregon
Grade = Non-Commercial (made for OSU)

Ultimate Analysis (dry weight basis)

% Carbon	= 54.16	% Hydrogen	= 5.93
% Oxygen	= 37.11	% Nitrogen	= .18
% Sulphur	= .07	% Chlorine	= 0.78
% Ash	= 2.55		

Proximate Analysis (dry weight basis)

% Fixed Carbon	= 25.85	% Volatile	= 71.60
% Ash	= same as in ultimate analysis		

Ash Fusion Data

Initial	= 2450.00 (°F)
H/W	= 2460.00 (°F)
1/2-H/W	= 2470.00 (°F)
Fluid	= 2480.00 (°F)

Additional Pellet Fuel Parameters

Rapeseed Supplement (% wet basis) ^a	= 0.50
Higher Heating Value	= 9284.34 (Btu/lbm)
Moisture Content (% wet basis)	= 8.00
Bulk Density	= 43.14 (lbm/ft ³)
Specific Density	= 79.70 (lbm/ft ³)
Mean Length	= .376 (inches)
Mean Diameter	= .314 (inches)

^aRapeseed was added in small percentages to some hogged biomass that was collected by OSU to be made into pellets. The rapeseed aids in pellet manufacture.

PELLET SAMPLE DATA

Pellet Code: 9

Pellet Species = Hemlock Fir and Sitka Spruce
(wood + bark)
Location of Raw Material = Southeast Coastal Alaska
Grade = Non-Commercial (made for OSU)

Ultimate Analysis (dry weight basis)

% Carbon	= 50.55	% Hydrogen	= 6.04
% Oxygen	= 40.40	% Nitrogen	= .35
% Sulphur	= .04	% Chlorine	= 0.19
% Ash	= 2.43		

Proximate analysis (dry weight basis)

% Fixed Carbon	= 24.27	% Volatile	= 73.30
% Ash	= same as in ultimate analysis		

Ash Fusion Data

Initial	= 2150.00 (°F)
H/W	= 2160.00 (°F)
1/2-H/W	= 2170.00 (°F)
Fluid	= 2195.00 (°F)

Additional Pellet Fuel Parameters

Rapeseed Supplement (% wet basis) ^a	= 0.25
Higher Heating Value	= 8799.78 (Btu/lbm)
Moisture Content (% wet basis)	= 14.40
Bulk Density	= 37.21 (lbm/ft ³)
Specific Density	= 75.32 (lbm/ft ³)
Mean Length	= .601 (inches)
Mean Diameter	= .305 (inches)

^aRapeseed was added in small percentages to some hogged biomass that was collected by OSU to be made into pellets. The rapeseed aids in pellet manufacture.

PELLET SAMPLE DATA

Pellet Code: 10

Pellet Species = Douglas Fir and Alder (wood + bark)
Location of Raw Material = Central Western Oregon
Grade = Non-Commercial (made for OSU)

Pellet Fuel Parameters

Higher Heating Value = 8960.40 (Btu/lbm)
Moisture Content (% wet basis) = 4.90
Bulk Density = 47.70 (lbm/ft³)
Specific Density = 81.76 (lbm/ft³)
Mean Length = .392 (inches)
Mean Diameter = .309 (inches)

PELLET SAMPLE DATA

Pellet Code: 11

Pellet Species = Cedar and Spruce (wood + bark)
Location of Raw Material = Central "Pan-Handle" Idaho
Grade = Commercial

Pellet Fuel Parameters

Higher Heating Value = 8964.52 (Btu/lbm)
Moisture Content (% wet basis) = 9.13
Bulk Density = 43.68 (lbm/ft³)
Specific Density = 81.08 (lbm/ft³)
Mean Length = .545 (inches)
Mean Diameter = .309 (inches)

PELLET SAMPLE DATA

Pellet Code: 12

Pellet Species = True Fir and Pine (wood and bark)
Location of Raw Material = Northwestern Montana
Grade = Commercial

Pellet Fuel Parameters

Higher Heating Value = 8850.21 (Btu/lbm)
Moisture Content (% wet basis) = 7.00
Bulk Density = 41.40 (lbm/ft³)
Specific Density = 81.56 (lbm/ft³)
Mean Length = .500 (inches)
Mean Diameter = .256 (inches)

PELLET SAMPLE DATA

Pellet Code: 13

Pellet Species = Douglas Fir and Ponderosa Pine
(wood + bark)
Location of Raw Material = Northwestern Montana
Grade = Commercial

pellet Fuel Parameters

Higher Heating Value = 8755.31 (Btu/lbm)
Moisture Content (% wet basis) = 4.60
Bulk Density = 44.77 (lbm/ft³)
Specific Density = 82.65 (lbm/ft³)
Mean Length = .495 (inches)
Mean Diameter = .314 (inches)

PELLET SAMPLE DATA

Pellet Code: 14

Pellet Species	= Douglas Fir and Ponderosa Pine (wood + bark)
Location of Raw Material	= Northwestern Montana
Grade	= Commercial

Pellet Fuel Parameters

Higher Heating Value	= 8637.99 (Btu/lbm)
Moisture Content (% wet basis)	= 6.90
Bulk Density	= 46.02 (lbm/ft ³)
Specific Density	= 81.64 (lbm/ft ³)
Mean Length	= .596 (inches)
Mean Diameter	= .317 (inches)

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APPENDIX C

MSW Fuel Data

ANCHORAGE, AK MSW—COMPOSITION

Anchorage, AK

Solid Waste	% by Weight
Food Waste	15.20
Lawn/Garden	6.50
Glass	7.00
Wood	1.20
Rocks/Ash	1.70
Paper	49.9
Ferrous Metals	9.25
Non-Ferrous Metals	1.25
Plastics/Leathers	5.90
Textiles	2.10
Total	100.00

JUNEAU, AK MSW-COMPOSITION

Juneau, AK

Solid Waste	Weight (lbs)	% by Weight	% Moisture
Food Waste	3.42	11.22	74.62
Lawn/Garden	0.23	0.77	70.94
Glass	2.55	8.38	—
Wood	0.49	1.61	20.00
Rocks/Ash	0.00	0.00	—
Paper			
Recyclable	3.43	11.26	52.17
Non-Recyclable	5.13	16.85	50.83
Corrugated	1.25	4.11	56.56
Metals	2.11	6.92	—
Plastics/Leathers	9.69	31.83	59.54
Textiles	2.15	7.06	48.99
Totals	30.44	100.00	57.15

BOISE, ID MSW-COMPOSITION

Boise, ID

Solid Waste	Weight (lbs)	% by Weight	% Moisture
Food Waste	0.42	2.02	54.78
Lawn/Garden	2.89	13.96	35.94
Glass	0.11	0.53	-
Wood	1.33	6.42	17.29
Rocks/Ash	6.29	30.39	-
Paper			
Recyclable	2.21	10.67	14.14
Non-Recyclable	2.19	10.60	19.57
Corrugated	0.10	0.49	23.53
Metals	1.40	6.77	-
Plastics/Leathers	2.54	12.25	5.00
Textiles	1.22	5.91	4.41
Totals	20.71	100.00	18.94

IDAHO FALLS, ID MSW-COMPOSITION

Idaho Falls, ID

Solid Waste	Weight (lbs)	% by Weight	% Moisture
Food Waste	0.69	3.06	55.37
Lawn/Garden	2.38	10.50	28.02
Glass	0.11	0.48	-
Wood	2.37	10.42	16.21
Rocks/Ash	1.13	4.96	-
Paper			
Recyclable	1.63	7.16	21.04
Non-Recyclable	6.56	28.86	15.31
Corrugated	2.83	12.45	15.90
Metals	0.54	2.39	-
Plastics/Leathers	3.35	14.75	13.29
Textiles	1.13	4.97	6.44
Totals	22.72	100.00	17.91

TWIN FALLS, ID MSW-COMPOSITION

Twin Falls, ID

Solid Waste	Weight (lbs)	% by Weight	% Moisture
Food Waste	6.32	22.83	74.99
Lawn/Garden	0.63	2.28	51.12
Glass	0.11	0.40	-
Wood	0.32	1.14	24.09
Rocks/Ash	2.54	9.17	-
Paper			
Recyclable	2.75	9.92	45.34
Non-Recyclable	3.11	11.23	40.86
Corrugated	1.15	4.14	43.02
Metals	3.60	13.03	-
Plastics/Leathers	6.18	22.35	14.09
Textiles	0.97	3.50	-
Totals	27.66	100.00	44.09

BILLINGS, MT MSW-COMPOSITION

Billings, MT

Solid Waste	Weight (lbs)	% by Weight	% Moisture
Food Waste	0.91	5.45	67.76
Lawn/Garden	4.18	25.05	57.93
Glass	0.04	0.21	-
Wood	0.07	0.43	18.06
Rocks/Ash	0.00	0.00	-
Paper			
Recyclable	3.54	21.23	21.38
Non-Recyclable	2.56	15.31	23.21
Corrugated	0.40	2.41	32.76
Metals	0.96	5.76	-
Plastics/Leathers	2.73	16.38	7.48
Textiles	1.30	7.77	27.45
Totals	16.70	100.00	32.46

HELENA, MT MSW-COMPOSITION

Helena, MT

Solid Waste	Weight (lbs)	% by Weight	% Moisture
Food Waste	5.31	12.85	43.07
Lawn/Garden	4.81	11.64	54.33
Glass	0.42	1.02	-
Wood	1.50	3.64	13.41
Rocks/Ash	0.64	1.54	-
Paper			
Recyclable	5.87	14.22	25.69
Non-Recyclable	7.76	18.78	36.98
Corrugated	2.01	4.87	20.29
Metals	0.00	0.00	-
Plastics/Leathers	12.31	29.81	36.94
Textiles	0.67	1.62	33.49
Totals	41.30	100.00	36.42

MISSOULA, MT MSW-COMPOSITION

Missoula, MT

Solid Waste	Weight (lbs)	% by Weight	% Moisture
Food Waste	3.92	8.91	60.84
Lawn/Garden	1.65	3.76	62.14
Glass	0.00	0.00	-
Wood	3.90	8.87	18.23
Rocks/Ash	6.86	15.61	-
Paper			
Recyclable	7.48	17.01	28.70
Non-Recyclable	4.25	9.67	20.30
Corrugated	3.25	7.40	43.53
Metals	5.00	11.38	-
Plastics/Leathers	5.47	12.45	16.40
Textiles	2.17	4.93	11.25
Totals	43.96	100.00	30.19

BEND-SISTERS, OR COMPOSITION

Bend-Sisters, OR

Solid Waste	Weight (lbs)	% by Weight	% Moisture
Food Waste	5.20	19.92	54.07
Lawn/Garden	0.00	0.00	0.00
Glass	1.49	5.72	-
Wood	0.71	2.72	16.22
Rocks/Ash	0.00	0.00	-
Paper			
Recyclable	11.34	43.46	52.60
Non-Recyclable	0.86	3.30	19.81
Corrugated	1.60	6.14	26.41
Metals	1.88	7.20	-
Plastics/Leathers	3.01	11.53	29.65
Textiles	0.00	0.00	0.00
Totals	26.08	100.00	45.67

Portland, OR

Solid Waste	% by Weight	% Moisture
Food Waste	8.80	
Lawn/Garden	10.00	
Glass	3.60	
Paper	34.80	
Disposable Diapers	1.50	
Plastics/Leathers	7.90	
Non-Ferrous Metals	1.10	
Ferrous Metals	6.00	
Wood	8.00	
Rocks/Ash	5.50	
Textiles	3.80	
Misc. Organics	6.70	
Other	2.50	
Total	100.00	23.06

CORVALLIS, OR COMPOSITION

Corvallis, OR

Solid Waste	Weight (lbs)	% by Weight	% Moisture
Food Waste	1.30	4.30	72.13
Lawn/Garden	3.25	10.76	53.86
Glass	0.35	1.16	-
Wood	3.60	11.92	11.24
Rocks/Ash	0.25	0.83	-
Paper			
Recyclable	9.80	32.45	20.64
Non-Recyclable	3.02	10.00	21.61
Corrugated	2.28	7.55	24.62
Metals	1.50	4.97	-
Plastics/Leathers	4.65	15.40	3.5
Textiles	0.20	0.66	21.43
Totals	30.20	100.00	23.25

WENATCHEE, WA MSW-COMPOSITION

Wenatchee, WA

Solid Waste	Weight (lbs)	% by Weight	% Moisture
Food Waste	4.61	14.60	71.87
Lawn/Garden	1.63	5.15	43.04
Glass	0.61	1.93	-
Paper			
Recyclable	2.94	9.32	37.34
Non-Recyclable	6.93	21.95	31.22
Corrugated	0.84	2.65	41.69
Rocks/Ash	0.71	2.25	-
Plastics/Leathers	5.43	17.20	12.91
Metals	2.53	8.02	-
Wood	3.98	12.59	19.27
Textiles	1.37	4.34	36.13
Totals	31.58	100.00	34.58

ASTM RDF Classifications

Class	Form	Description
RDF-1	Raw (MSW)	Municipal solid waste as a fuel in an as-discarded form without oversize bulky waste
RDF-2	Coarse (cRDF)	MSW processed to coarse particle size with or without ferrous metal separation, such that 95% by weight passes through a 6-inch-square mesh screen
RDF-3	Fluff (fRDF)	Shredded fuel derived from MSW processed for the removal of metal, glass, and other entrained organics; particle size of this material is such that 95% by weight passes through a 2-inch-square mesh screen; also called "fluff RDF"
RDF-4	Powder (pRDF)	Combustible waste fraction processed into powdered form, 95% by weight passing through a 10-mesh screen (0.05-inch square)
RDF-5	Densified (dRDF)	Combustible waste fraction densified (compressed) into pellets, slugs, cubettes, briquettes, or similar forms
RDF-6	Liquid	Combustible waste fraction processed into a liquid fuel
RDF-7	Gas	Combustible waste fraction processed into a gaseous fuel

Source: The American Society of Testing and Materials (E-38.01, #-776 to E-791-81); and ANL/CNSV-TM-120, Vol. 4

Sorting and Ultimate Analysis of RDF Types

Property	Coarse RDF	Wet RDF	Fluff RDF	Powdered RDF
Sorting Analysis^b (%)				
Paper	45.5	29.9	74.0	71.7
Plastics	3.2	2.3	3.4	4.6
Rubber, Leather	2.1	1.6	1.9	2.1
Wood	3.2	2.3	2.8	3.0
Textiles	3.2	2.2	4.3	4.8
Yard Waste	10.5	4.9	9.4	6.2
Food	10.6	3.4	3.0	3.6
Fines	10.5	3.4	0.6	1.6
Glass, Ceramics	9.6	0	0.04	0
Metals				
Ferrous	0.3	0	0.21	0
Aluminum	0.7	0	0.01	0
Other Nonferrous	0.3	0	0.07	0
Moisture	—	50.0 ^c	—	—
Total	100.0	100.0	100.0	100.0
Ultimate Analysis (%)				
Moisture	26.4	50.0	25.2	2.0
Carbon	26.8	22.0	33.8	44.1
Hydrogen	3.6	3.0	4.5	5.9
Oxygen	21.3	17.5	27.9	36.1
Nitrogen	0.5	0.4	0.5	0.7
Chlorine	0.5	0.4	0.5	0.7
Sulfur	0.2	0.1	0.2	0.3
Inorganic Matter	20.7	6.6	7.3	10.2
Total	100.0	100.0	100.0	100.0
Higher Heating Value				
HHV (Btu/lb)	4677	3835	5841	7556