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Properties of Wood for Combustion Analysis

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Abstract

A systematic compilation of 21 different property values of wood and bark fuel was made to facilitate the engineering analysis and modeling of combustion systems. Physical property values vary greatly and properties such as density, porosity, and internal surface area are related to wood species whereas bulk density, particle size, and shape distribution are related to fuel preparation methods. Density of dry wood and bark varies from 300 to 550 kg m^{-3}*; bulk density of prepared wood fuel varies from about 160 to 230 kg* m^{-3}*. Thermal property values such as specific heat, thermal conductivity, and emissivity vary with moisture content, temperature, and degree of thermal degradation by one order of magnitude. The carbon content of wood varies from about 47 to 53% due to varying lignin and extractives content. Mineral content of wood is less than 1%, but it can be over 10 times that value in bark. The composition of mineral matter can vary between and within each tree. Properties that need further investigation are the temperature dependency of thermal conductivity and the thermal emissivity of char-ash. How mineral matter is transformed into various sizes of particulates is not well understood.*

Key words: Wood, combustion, fuel properties, modeling.

NOMENCLATURE

A_C	Pre-exponential factor for char
A_{CO}	Pre-exponential factor for CO
A_{HC}	Pre-exponential factor for hydrocarbons
A_P	Pre-exponential factor for pyrolysis (h^{-1})
A_V	Surface area per unit volume (cm^{-1})
c	Specific heat (J $kg.^{-1}$ K^{-1})
D	Diffusivity of oxygen (m^2 s^{-1})
E_C	Activation energy for char (cal mol^{-1})
E_{CO}	Activation energy for CO (cal mol^{-1})
E_{HC}	Activation energy for hydrocarbons (cal mol^{-1})
E_P	Activation energy for pyrolysis (cal mol^{-1})
G_g	Mass flux of gas (kg $m^{-2}h^{-1}$)
$\tilde{h}_D$	Mass transfer coefficient (kg s^{-1} m^{-2})
k	Thermal conductivity (W m^{-1} K^{-1})
k_r	Rate constant
M	Moisture mass fraction
M'	Molecular weight (kg $kgmol^{-1}$)
r	Pressure (atm)
R	Universal gas constant (cal mol^{-1} K^{-1})
Re	Reynolds number
R_{HC}	Hydrocarbon reaction rate (kgmol m^{-3})
R_C	Char reaction rate (kg s^{-1})
R_{CO}	CO reaction rate (kgmol m^{-3})
R_p	Pyrolysis rate (kg s^{-1})
S	Specific gravity
Sc	Schmidt number
T_g	Solid temperature (K)
δ	Void fraction
r_c	Char density (kg m^{-3})
r_g	Density of gas phase (kg m^{-3})
r_s	Solid density (kg m^{-3})
μ	Viscosity (N s m^{-2})
[ ]	Species concentration (kgmol m^{-3})

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INTRODUCTION

Analysis and modeling of combustion in stoves, furnaces, boilers and industrial processes require adequate knowledge of wood properties. Detailed computer modeling of combustion processes requires accurate property values, and these properties are not generally available in one reference source. The objectives of this paper are to review existing property data on wood which are needed for the analysis of combustion systems and to suggest properties that need further quantification.

Fuel properties for combustion analysis of wood can be conveniently grouped into physical, thermal, chemical, and mineral properties. Bark properties should be distinguished from wood properties. Thermal degradation products of wood consist of moisture, volatiles, char and ash. Volatiles are further subdivided into gases and tars. Some properties vary with species, location within the tree, and growth conditions. Other properties depend on the combustion environment. Where the properties are highly variable, the likely range of the property is given. Hence, this paper is a general review of properties rather than a tabulation of specific data.

Combustion systems using wood fuel may be generally grouped into fixed bed, suspension burning, and fluidized bed systems. The systems range from residential to commercial and industrial to utility scale. The fuel property data needed depend. of course. on the type of application and the detail of the model. In general, combustion models can be classified as macroscopic or microscopic. Wood fuel properties for macroscopic analysis, such as ultimate analysis, heating value. moisture content, particle size, bulk density, and ash fusion temperature, have recently been reviewed (Bushnell et al., 1989). Properties for microscopic analysis include thermal, chemical kinetic, and mineral data, and these properties have not been collected in one source for wood. Although there is a risk of oversimplifying complex processes, the authors hope that the information provided will assist the combustion modeler in the difficult job of assembling property data. The paper is not a comprehensive review of all available wood fuel property data, but rather gives a data set sufficient for modeling purposes.

PHYSICAL PROPERTIES

Physical properties for analysis of combustion systems include density, hulk density, particle size, internal and external surface area per unit volume, porosity, and color.

The density of commercially important wood species in the United States ranges from 300 to 550 kg m^{-3} on an ovendry basis (Forest Products Laboratory. 1987). The range in density of bark is similar (Koch, 1972). Tropical woods vary more widely. with a dry density as high as 1040 kg m^{-3}. For a particular species, the variation in dry density is not more than about 10%. The density of the wood cell wall is 1450 to 1550 kg m^{-3} (Weatherwax & Tarkow, 1968). With increasing moisture content, both the density and volume increase up to the fiber saturation point of about 30% moisture. Above this point, only the density increases (Forest Products Laboratory, 1987). Fresh. green wood has a moisture content of 35-60%, on a wet basis. Dried wood used for fuel typically has a moisture content of 5-20%.

The particle size of wood fuels ranges from whole trees to sander dust and includes processed and pelletized fuels. Dry bulk density, which is defined as mass of ovendry wood per unit of green bulk volume. ranges from 157 kg m^{-3} for hardwood shavings to 227 kg m^{-3} for hardwood sawdust (Table 1) (Forest Products Laboratory, 1987). Approximately 80% of the sawdust is smaller than 2·5 mm and 80% of the pulp chips and hog fuel are less than 25 mm and 30 mm, respectively, based on the particle width (Fig. 1) (Seppanen, 1988). Of course, the size distributions vary with the equipment used to make the chips. Representative shape factors (length to thickness ratio) for sawdust, pulp chips, and hog fuel, are 3·5, 5·8 and 35, respectively (Seppanen, 1988).

The porosity and internal surface area of wood char are needed for detailed modeling of pulverized wood combustion. Upon completion of pyrolysis, the porosity of char is 0·8-0·9 for wood heated under combustion conditions. The initial char density is 10-20% that of the dry wood.

Table 1. Representative dry bulk density of typical wood fuels (Forest Products Laboratory, 1987)

Fuel type	*Bulk density (kg m^{-3})*
Hardwood sawdust and bark	227
Mixed pine-hardwood sawdust	219
Clean hardwood pulp chips	210
Hardwood whole-tree chips	211
Pine whole-tree chips	181
Hogged dry trims (hardwood)	221
Shavings (hardwood)	157

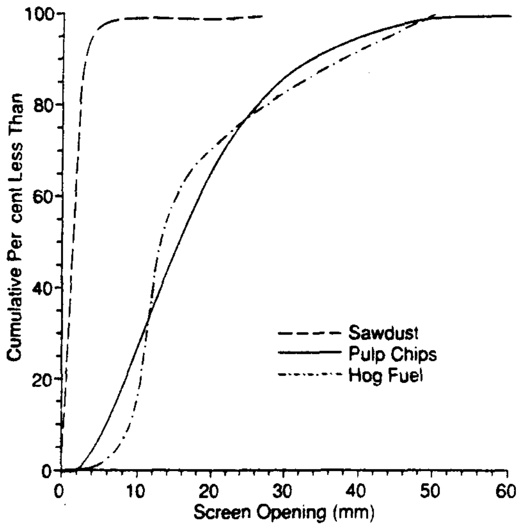

Fig. 1. Cumulative size distribution for sawdust, unscreened pulp chips and hog fuel.

depending on the heating rate. As the char reacts. the density decreases further. The internal surface area of wood char (Wark & Warner, 1981) is of the order of 10^6 m^2 kg^{-1}. The pore size distribution of wood char (Baileys & Blankenhorn, 1982) ranges from 0·01 to 30 μm. For packed bed combustion of pulp chips, the void fraction and external surface area per unit total volume are used in some models. For pulp chips, the void fraction is 0·5-0·6, and the surface area per unit total volume (Ragland, K. W., Aerts, D. J. & Baker, A. J., unpublished) is about 1·5 cm^{-1}.

When heated, wood changes color. At 250°C, wood is dark brown; above 300°C, wood is black. The brown color is associated with the onset of pyrolysis. Above 300°C, shrinkage also begins (Baileys & Blankenhorn, 1982).

THERMAL PROPERTIES

Important thermal properties in the analysis of wood combustion include the specific heat of wood and char, the thermal conductivity of wood and char, and the emissivity of char. Specific heat depends on temperature and moisture content but not on density or species. The specific heat of dry wood is given by (TenWolde *et al.*, 1988)

$$c(\text{dry}) = 0{\cdot}1031 + 0{\cdot}003867T \qquad (\text{kJ kg}^{-1}\ \text{K}^{-1}) \qquad (1)$$

The specific heat of wet wood is greater than would be expected from the simple law of mixture as a result of the energy absorbed by the wood-water bonds and can be represented by a correction term (TenWolde *et al.*, 1988)

$$c(\text{wet}) = [c(\text{dry}) + 4{\cdot}19M]/(1+M) + A \qquad (\text{kJ kg}^{-1}\ \text{K}^{-1}) \qquad (2)$$

where

$A = (0{\cdot}02355T - 1{\cdot}32M - 6{\cdot}191)M$,
T = temperature in K, and
M = fractional moisture content. dry basis.

Above the fiber saturation point, $A = 0$. Specific heat can vary by as much as 100% depending on the temperature and moisture content (Table 2).

The specific heat of wood char can reasonably be assumed to be the same as that of graphite. The specific heat of graphite varies from 0·715 kJ kg^{-1} K^{-1} at 300 K to 2·04 kJ kg^{-1} K^{-1} at 2000 K. A curve fit of the data from 700 to 2000 K, which holds to within 5%, is given by (Stull, 1971)

$$c(\text{char}) = 1{\cdot}39 + 0{\cdot}00036T \qquad (\text{kJ kg}^{-1}\ \text{K}^{-1}) \quad (3)$$

The thermal conductivity of wood increases with density, moisture content. and temperature. Also, the thermal conductivity is approximately 1·8 times greater parallel to the grain than in either the radial or tangential directions. For a wide variety of wood species at room temperature. the average thermal conductivity perpendicular to the grain (TenWolde *et al.*, 1988) is given by

$$k = S(0{\cdot}1941 + 0{\cdot}4064M) + 0{\cdot}01864 \qquad (\text{W m}^{-1}\ \text{K}^{-1}) \qquad (4)$$

where S is the specific gravity based on volume at the current moisture content and weight when ovendry. For example, if $S = 0{\cdot}47$ and $M = 0{\cdot}10$, $k = 0{\cdot}129$ W m^{-1} K^{-1}. The thermal conductivity of wood increases with temperature at the rate of approximately 0·2% per °C above room temperature. Hence, thermal conductivity increases 10% for every 50 K increase in temperature. The tem-

Table 2. Specific heat of wood for selected temperatures and moisture contents

Temperature (K)	*Specific heat (kJ kg^{-1} K^{-1})*			
	c(dry)	*c(5%)*	*c(12%)*	*c(20%)*
280	1·2	1·3	1·5	1·7
300	1·3	1·4	1·7	1·9
320	1·3	1·5	1·8	2·0
340	1·4	1·6	1·9	2·2
360	1·5	1·7	2·0	2·3

perature correction is based on limited data, however and should be used with caution.

The thermal conductivity of char is reported to be 0·052 W m^{-1} K^{-1} at room temperature for maple, beech, and birch char (Wheast, 1976). Intuitively, the thermal conductivity of char depends on density, which depends on the heating rate. Evans and Emmons (1977) report that the thermal conductivity is given by

$$k = 0 \cdot 67S - 0 \cdot 071 \quad (\mathrm{W\ m^{-1}\ K^{-1}}) \qquad (5)$$

where S is the specific gravity as noted above. Obviously. this relation fails at $S < 0 \cdot 106$. The variation of char conductivity with temperature is not available.

The thermal radiation emissivity of carbon is 0·80 and is independent of temperature (Anon.. 1972*a*). Actual wood char may have a lower emissivity resulting from the ash layer on the surface of the char. The character of the ash layer depends on temperature, flow velocity, and oxygen concentration; therefore, char emissivity is difficult to assess. Refractory oxides typically have an emissivity of about 0·4 at 1300 K, for example, and wood ash emissivity may be similar. A char emissivity of 0·75 has been used for modeling purposes (Evans & Emmons, 1977).

CHEMICAL PROPERTIES

Important chemical properties for combustion are the ultimate analysis, proximate analysis, analysis of pyrolysis products, overall heating value. heat of pyrolysis, heating value of the volatiles, and heating value of the char.

The ultimate analysis (Table 3) provides weight percentage of C, H, O, N, and S. The C content of softwood species is 50-53%, and that of hardwood species 47-50% due to the varying lignin and extractives content. All wood species contain about 6% H (Petura, 1979). Oxygen content ranges from 40% to 44%, S is less than 0·1% and N ranges from 0·1 -0·2%.

Proximate analysis gives the weight fraction of moisture, and volatiles including tar. char. and ash. according to ASTM standard test method E870-82. The ground wood sample is heated in air to 103°C to constant weight to obtain dry wood, to 950°C in a capped crucible to obtain char. and to 600°C in air to obtain ash. The volatile yield can be increased by increasing the heating rate (i.e. increasing the heat transfer rate or increasing the exposed surface area). Conversely, the char yield is increased by slow heating of large particles. The standard procedure for proximate analysis is more representative of combustion on a grate than in suspension. The ASTM volatile yield for dry ash-free wood ranges from 70% to 90%, depending on the species. The ASTM volatile yield for bark is typically closer to 70%.

The volatile yield of dry wood under combustion conditions may be further subdivided into light hydrocarbons. tar. carbon monoxide, carbon dioxide, hydrogen. and moisture yield (Table 4). The yields depend on the temperature and heating rate of pyrolysis. The tar has an average composition (Adams. 1980) of $C_6H_{6 \cdot 2}O_{0 \cdot 2}$, and the light hydrocarbons are primarily methane.

The higher heating value of different wood species on a moisture-free basis varies less than 15%. The higher heating value of softwoods (Baker. 1989) is 20-22 MJ kg^{-1} and of hardwoods, 19-21 MJ kg^{-1}. The average higher heating value of seven *Populus* hybrids (Bowersox *et al.*, 1979) is 19·49 MJ kg^{-1}. Typically, softwoods have more extractives and more lignin than do hardwoods, which accounts for the slightly higher heating value.

The heating value of the volatiles may be estimated by the following method. Pyrolysis is

Table 3. Ultimate analysis of wood (dry, ash-free weight percent)

Element	*Average of 11 hardwoods*[a]	*Average of 9 softwoods*[a]	*Oak bark*[b]	*Pine bark*[b]
C	50·2	52·7	52·6	54·9
H	6·2	6·3	5·7	5·8
O	43·5	40·8	41.5	39·0
N	0·1	0·2	0·1	0·2
S	—	0·0	0·1	0·1

[a] Tillman *et al.* (1981).
[b] Anon. (1972*b*).

Table 4. Distribution of pyrolysis products for dry wood under combustion conditions[a]

product	*Mass fraction*
H_2O	0·25
CO	0·183
CO_2	0·115
H_2	0·005
Light hydrocarbons	0·047
Tar	0·20
Char	0·20

[a] Bowersox *et al.* (1979) and Forests Products Laboratory (1987).

initially slightly endothermic and then exothermic, so that overall pyrolysis is considered essentially thermally neutral (Roberts, 1971). Using the data in Table 4 and assuming that char is all carbon with a higher heating value of 32·8 MJ kg^{-1}, an average higher heating value of the volatiles is calculated to be 16·2 MJ kg^{-1}. Subtracting the heating value of CO and H_2, the light hydrocarbons and tars have a higher heating value of 41·0 MJ kg^{-1}.

Above 700°C char contains little hydrogen. Stimely and Blankenhorn (1985) reported the hydrogen content of char as a function of temperature for four woods. For example, for hybrid poplar, the percentage of hydrogen by weight is

$$H_2 = 7{\cdot}39\text{-}0.01\, T \qquad (6)$$

where T is the final carbonization temperature (°C). Hence for temperatures above 739°C, which is typically the case for most combustion applications, char does not contain hydrogen.

REACTION RATES

To analyze combustion systems, it is often useful to model the rate at which drying, pyrolysis, and char burn take place. Drying rates are outside the scope of this paper. During pyrolysis the components of wood. such as cellulose, hemicellulose, and lignin, pyrolyze at different rates; however, for combustion analysis, a single global rate expression of the Arrhenius form often gives acceptable results (Table 5). Roberts (1970) reviewed the literature on the pyrolysis of wood and suggested that an activation energy of 31 kcal mol^{-1} is appropriate for both small and large particles (Table 6); a conclusion that was supported by Belleville (1984). The suggested pre-exponential constant (Roberts, 1970; Belleville, 1981) in the Arrhenius equation is 7 × 10^7 s^{-1}. As noted previously, the pyrolysis gases contain hydrogen, carbon monoxide, light hydrocarbons and tars. The hydrogen can be considered to react instantaneously at combustion temperatures. The global oxidation rate of CO to CO, is well known and depends on the concentration of water vapor (Table 5). Global kinetic reaction rates for hydrocarbon volatiles from wood combustion are not available. Smoot and Smith (1985) have reviewed the kinetics for coal volatiles, and their results indicated that long-chain and cyclic hydrocarbons react to form hydrogen and carbon monoxide according to the following global reaction:

$$C_nH_m + 0{\cdot}5nO_2 = 0{\cdot}5mH_2 + nCO$$

Light hydrocarbons and tars are lumped together in this approach.

Table 5. Reaction rate equations

Rate equation	*Reference*
$R_p = A_p\,(r_s - r_c)\exp(-E_p/RT_s)$	Roberts (1970)
$R_c = (A_v r^{n}_{O_2}(M'_g/M'_s)\,k_r + 2\tilde{h}_D)/((M'_g/M'_s)\,k_r + 2\tilde{h}_D)$	Smoot and Smith (1985)
$R_{HC} = A_{HC}\; T_g r^{0\cdot3}[HC]^{0\cdot5}[O2]\exp(-E_{HC}/RT_g)$	Smoot and Smith (1985)
$R_{CO} = ACO[CO]\;\; [O_2]^{0\cdot25}[H_2O]^{0\cdot5}\exp(-E_{CO}/RT_g)$	Smoot and Smith (1985)
where	
$k_r = A_c\exp(-E_c/RT_s)$	
$\tilde{h}_D = 1{\cdot}46\, r_{N_2}\; M'_g G_g S_c^{-2/3} Re^{-0\cdot41}(1 - d)^{0\cdot2}$	Gamson (1951)
$Re = G_g/(A_v(1-\delta)\mu)$; $\quad Sc = \mu/r_g$	

Table 6. Reaction rate constant values for equations in Table 5

Parameter	*Value*	*Reference*
A_p	2·52 × 10^{11} h^{-1}	Roberts (1970)
E_p	3·1 × 10^4 cal mol^{-1}	Roberts (1970)
A_{CO}	4·0 × 10^5 (see reaction rate)	Smoot and Smith (1985)
E_{CO}	4·10 × 10^4(cal mol^{-1})	Smoot and Smith (1985)
A_{HC}	2·07 × 10^4(see reaction rate)	Smoot and Smith (1985)
E_{HC}	1·917 × 10^7 cal mol^{-1}	Smoot and Smith (1985)
A_C	1·71 × 10^7 kg m^{-2}h^{-1}	Bhagat (1980)
E_C	23·8 × 10^4 cal mol^{-1}	Bhagat (1980)

Char reacts with oxygen, carbon dioxide, water and hydrogen. Char oxidation is the dominant reaction in a combustion environment. Since this is a surface reaction. the reaction rate depends on kinetics and diffusion of oxygen to the char surface (Tables 5 and 6). Minimal wood-char kinetic data are available compared to coal-char data, although this is important because char burnout is much longer than volatile burnout. The diffusion parameters depend on the gas conditions and are beyond the scope of this paper. as is the use of intrinsic kinetic data instead of global kinetics.

MINERAL PROPERTIES

The mineral content of clean wood of temperate tree species is 0.1% to 06% and that of bark 3% to 5%. Mineral matter in wood consists mostly of salts of calcium, potassium, and magnesium. but salts of many other elements are also present in lesser amounts (Table 7). Some salts are formed with the organic acid groups of the cell wall components. whereas others occur as carbonates. phosphates, sulfates, silicates and oxalates. The mineral content of wood and bark is highly variable between and within species and can vary with soil and growth rate. Whole-tree analyses of minerals and trace elements in aspen. pine bark. and oak bark (Table 8) are different from that of pure wood. Silica is rarely present in more than trace amounts in the wood of temperate tree species (Pettersen, 1984). The silica content of clean bark is higher than that of wood. Analysis of bark from 18 softwood species and 24 hardwood species indicated an average silica content of 0·05% and 0·11%, respectively (Harder & Einspahr, 1980). The silca content of bark. as used for fuel. however. is higher because of soil contamination by wind and harvesting methods.

Table 7. Mineral analysis of wood

Element	*Mineral content (ppm)*		
	Yellow Poplar^a	*White Oak*^{a}	*Loblolly Pine*^{b}
Ca	1182	1976	1141
K	517	1128	116
Mg	265	294	326
Na	258	216	230
P	108	75	40
Mn	48	59	121
Fe	35	70	72
Al	14	32	—
Cu	3	2	—
Zn	8	62	—

^{a}Koch (1985).
^{b}Koch (1972).

Table 8. Mineral analysis of whole tree and bark

Element	*Mineral content (ppm)*		
	Aspen (whole tree)^a	*Pine bark*^{b}	*Oak bark*^{c}
Ca	4160	5282	24418
K	1424	1333	88
Mg	493	1137	3816
P	323	—	—
S	107	—	—
Fe	30	609	1224
Zn	36	—	—
Mn	17	—	—
Al	10	2149	29
B	6	—	—
Cu	13	—	—
Na	17	280	3500
Pb	1·4	—	—
Cd	0·30	—	—
Si	—	5278	2745

Total ash: ^{a} = 1·45%: ^{b} = 2·9%: ^{c} = 5·3%.

Ash is formed from mineral matter during combustion and gasification. The ash yield of wood grown in the temperate zones is 0·1-1·0%, whereas wood grown in the tropics contains up to 5% ash (Fengel & Wegener, 1984). Bark contains 3-8%, ash. Wood ash typically includes 40-70% calcium oxide and 10-30% potassium oxide.

During combustion. the mineral ions oxidize and volatilize or form particulates. The char surface is hotter than the gas or the interior of the particle. and ash particles tend to form on the char surface. As the char burns away, the ash particles are released. Knowledge of mineral matter behavior is needed for analysis of ash deposition, erosion and corrosion in combustion systems, as well as for understanding stack gas opacity.

The ash-fusion temperature, which is measured in the laboratory by ASTM method D 1857, is used as an indicator of deposition tendency in actual combustion systems (Table 9). The ash-fusion temperature is determined by mixing the ash sample from proximate analysis with a solution of dextrin to form a stiff paste that is pressed into small cone-shaped molds. The oven temperature at which the cone first deforms is reported as the onset of ash fusion. In addition to the initial deformation temperature, the softening temperature, hemispherical temperature, and fluid temperature are reported. Both oxidizing (air) and

Table 9. Ash-fusion temperatures for wood and bark

Source of ash	*Reducing temperature (°C)*	*Oxidizing temperature (°C)*
Wood [a]		
Initial deformation	1450-1515	—
Fluid	1500-1550	—
Oak bark [b]		
Initial deformation	1477	1471
Softening	1493	1499
Fluid	1504	1510
Pine bark [b]		
Initial deformation	1193	1210
Softening	1226	1249
Fluid	1266	1288

[a] Baumeister *et al.* (1978).
[b] Anon. (1972*b*).

reducing (60% CO, 40% CO_2) atmospheres are used. Wood has a higher ash-fusion temperature than do many coals (Anon., 1972*b*) and hence can sometimes be less prone to ash deposition than coal. However, detailed testing is required to investigate fouling. slagging and agglomeration.

CONCLUDING REMARKS

Property values for the analysis of combustion of wood fuels have been collected and are reviewed in this paper. Selected properties arc given for unheated wood and bark and for the thermal degradation products of volatiles, char and ash. In some geographical locations, bark is the main wood fuel; generally, less basic data on bark are available when compared to available data on wood.

Physical properties of density, size. and surface area per unit volume are presented for various types of wood fuels. The thermal properties of specific heat and thermal conductivity of wood and char are well known; however. the temperature dependency of the char thermal conductivity is not known. The thermal emissivity of char-ash is not well known. Overall heating values and elemental analyses are readily available. Pyrolysis product yields are highly dependent on heating conditions. Depending on the actual conditions, the standard proximate analysis may or may not be applicable. Suggestions arc made above for approximating the volatile reaction rates, but further investigation in this area is needed. Global char reaction rates also need further observation. Mineral matter in wood is well characterized. Little is known. however. on how the mineral matter is transformed into particulate ash of various sizes.

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