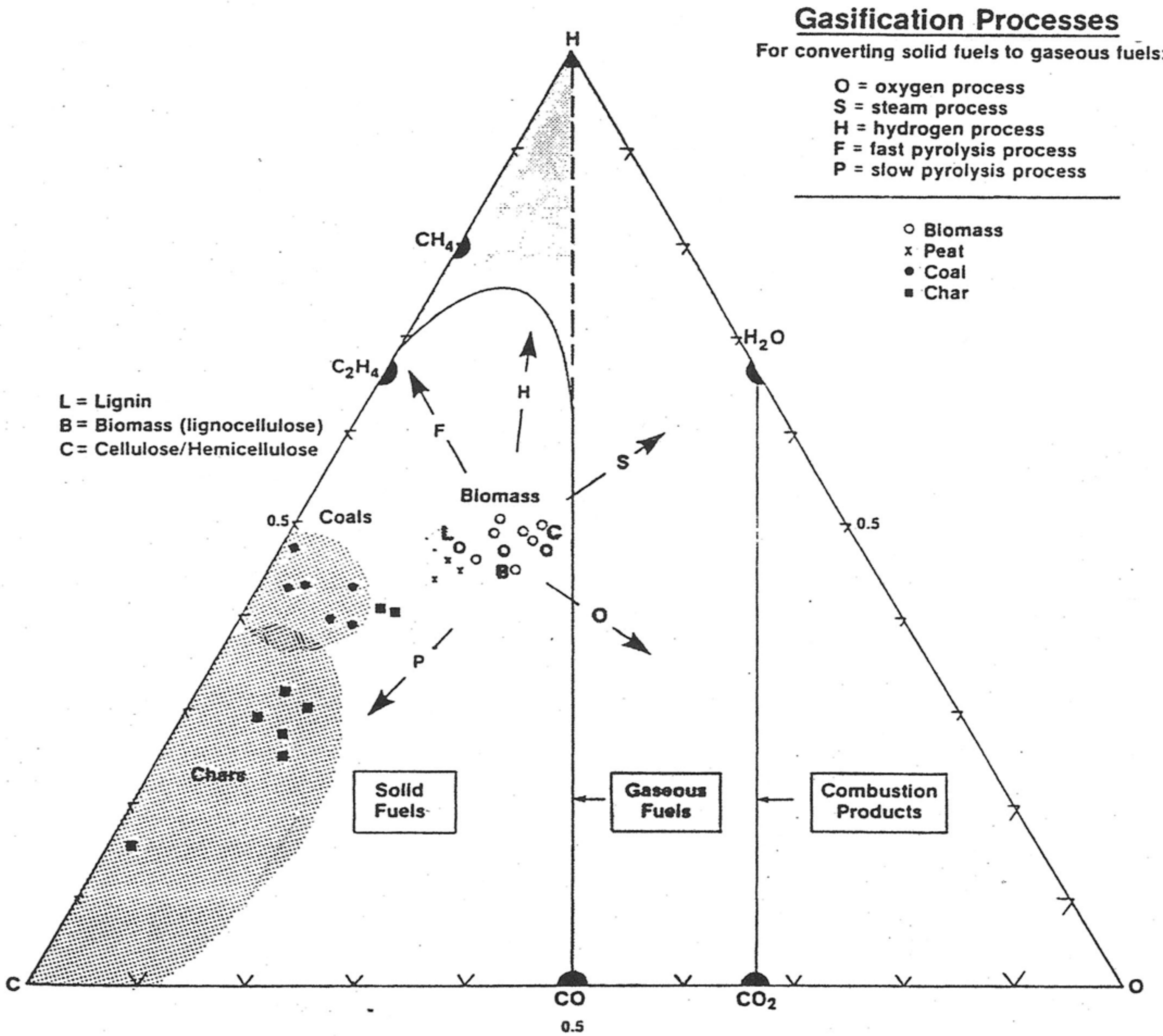
ALL POWER LABS
GASIFIER EXPERIMENTERS KIT

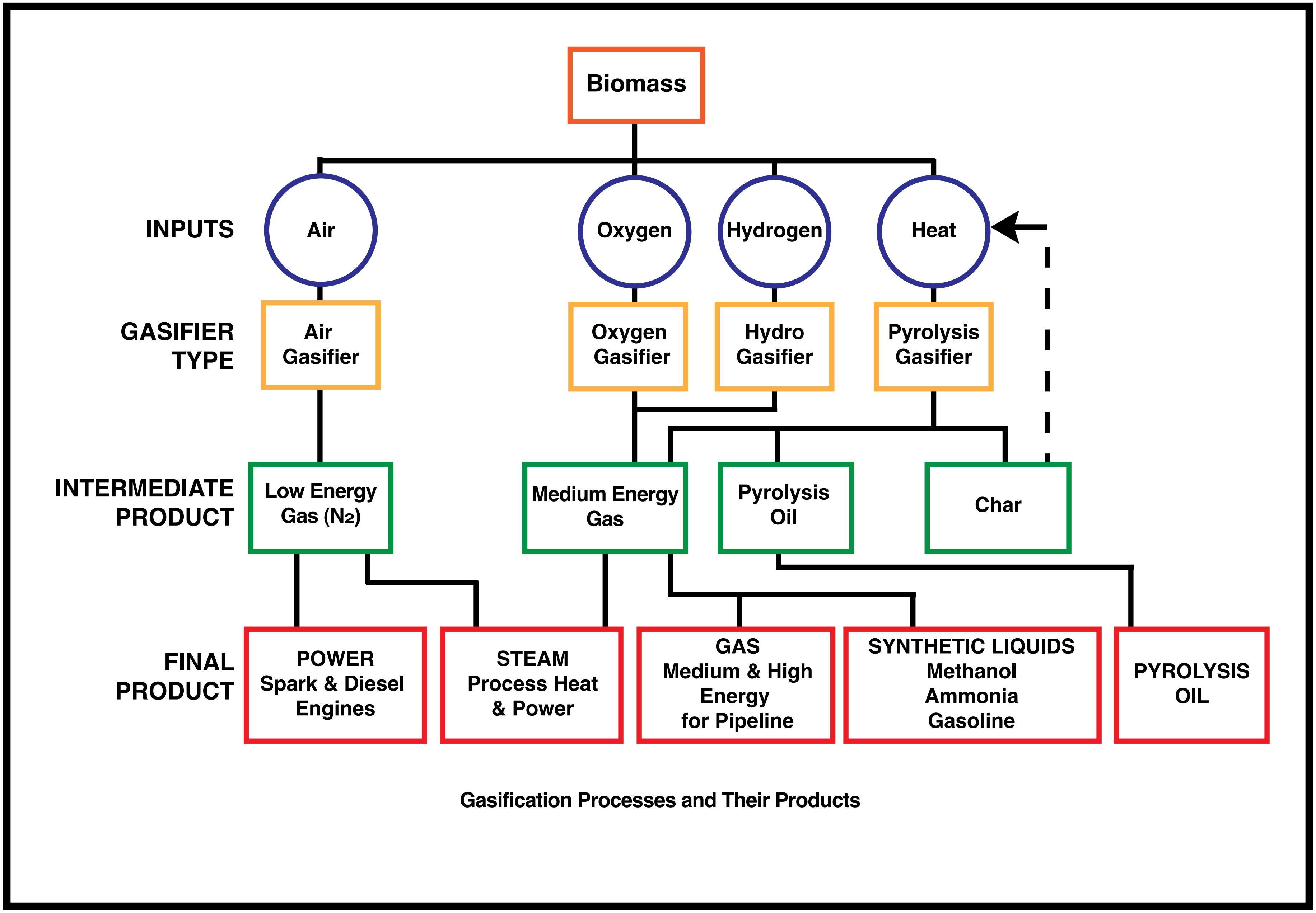
Science Addendum

Directions of Chemical Change During Biomass Gasification



(Source: Reed, 1981)

Pathways of Biomass Energy



Gasification Processes and Their Products

Adapted from Tom Reed

Energy Content of Fuel Gases and Their Uses

Name	Source	Energy Range (Btu/SCF)	Use
Low Energy Gas (LEG) [Producer Gas, Low Btu Gas]	Blast Furnace, Water Gas Process	80-100	On-site industrial heat and power, process heat
Low Energy Gas (LEG) [Generator Gas]	Air Gasification	150-200	Close-coupled to gas/oil boilers Operation of diesel and spark engines Crop drying
Medium Energy Gas (MEG) [Town Gas; Syngas]	Oxygen Gasification Pyrolysis Gasification	300-500	Regional industrial pipelines Synthesis of fuels and ammonia
Biogas	Anaerobic Digestion	600-700	Process heat, pipeline (with scrubbing)
High Energy Gas (HEG) [Natural Gas]	Oil/Gas Wells	1000	Long distance pipelines for general heat, power, and city use
Synthetic Natural Gas (SNG)	Further Processing of MEG and Biogas	1000	Long distance pipelines for general heat, power, and city use

Source: T. Reed, 1979

Table 1.10. Combustion characteristics of fuels* (See also Tables 1.7, 1.9, 2.1, 2.12, and 3.1)

Fuel	Minimum ignition temp, F/C	Calculated flame temperature,† F/C		Flammability limits % fuel gas by volume		Maximum flame velocity, fps and m/s		% Theoretical air for max. flame velocity
		in air	in O_2	lower	upper	in air	in O_2	
Acetylene, C_2H_2	581[c]/305	4770/2632	5630/3110	2.5	81.0	8.75/2.67	—	83
Blast furnace gas	—	2650/1454	—	35.0[h]	73.5	—	—	—
Butane, commercial	896/480	3583/1973	—	1.86	8.41	2.85/0.87	—	—
Butane, n-C_4H_{10}	761/405	3583/1973	—	1.86	8.41	1.3/0.40	—	97
Carbon monoxide, CO	1128[c]/609	3542[h]/1950	—	12.5[f]	74.2[f]	1.7/0.52	—	55
Carbureted water gas	—	3700/2038	5050/2788	6.4	37.7	2.15/0.66	—	90
Coke oven gas	—	3610/1988	—	4.4[f]	34.0[f]	2.30/0.70	—	90
Ethane, C_2H_6	882[c]/472	3540/1949	—	3.0	12.5	1.56/0.48	—	98
Gasoline	536[f]/280	—	—	1.4	7.6	—	—	—
Hydrogen, H_2	1062[c]/572	4010/2045	5385/2974	4.0	74.2	9.3/2.83	—	57
Hydrogen sulfide, H_2S	558[f]/292	—	—	4.3	45.5	—	—	—
Mapp gas, C_3H_4‡	850/455	—	5301/2927	3.4	10.8	—	15.4/4.69	—
Methane, CH_4	1170[c]/632	3484/1918	—	5.0	15.0	1.48[a]/0.45	14.76/4.50	90
Methanol, CH_3OH‡	725/385	3460/1904	—	6.7	36.0	—	1.6/0.49	—
Natural gas	—	3525[g]/1941	4790[g]/2643	4.3	15.0	1.00/0.30	15.2/4.63	100
Producer gas (See Part 3)	—	3010/1654	—	17.0[f]	73.7	0.85/0.26	—	90
Propane, C_3H_8	871/466	3573/1967	5130/2832	2.1	10.1	1.52/0.46	12.2/3.72	94
Propane, commercial	932/500	3573/1967	—	2.37	9.50	2.78/0.85	—	—
Propylene, C_3H_6	—	—	5240/2893	—	—	—	—	—
Town gas (Br. coal)[d]	700/370	3710/2045	—	4.8‡	31.0	—	—	—

* For combustion with air at standard temperature and pressure. These flame temperatures are calculated for 100% theoretical air, dissociation considered. Unless otherwise noted, data is from Reference 1.i.

† Flame temperatures are theoretical—calculated for stoichiometric ratio, dissociation considered.

‡ From private communications.

Small letters refer to references at end of Part 1.

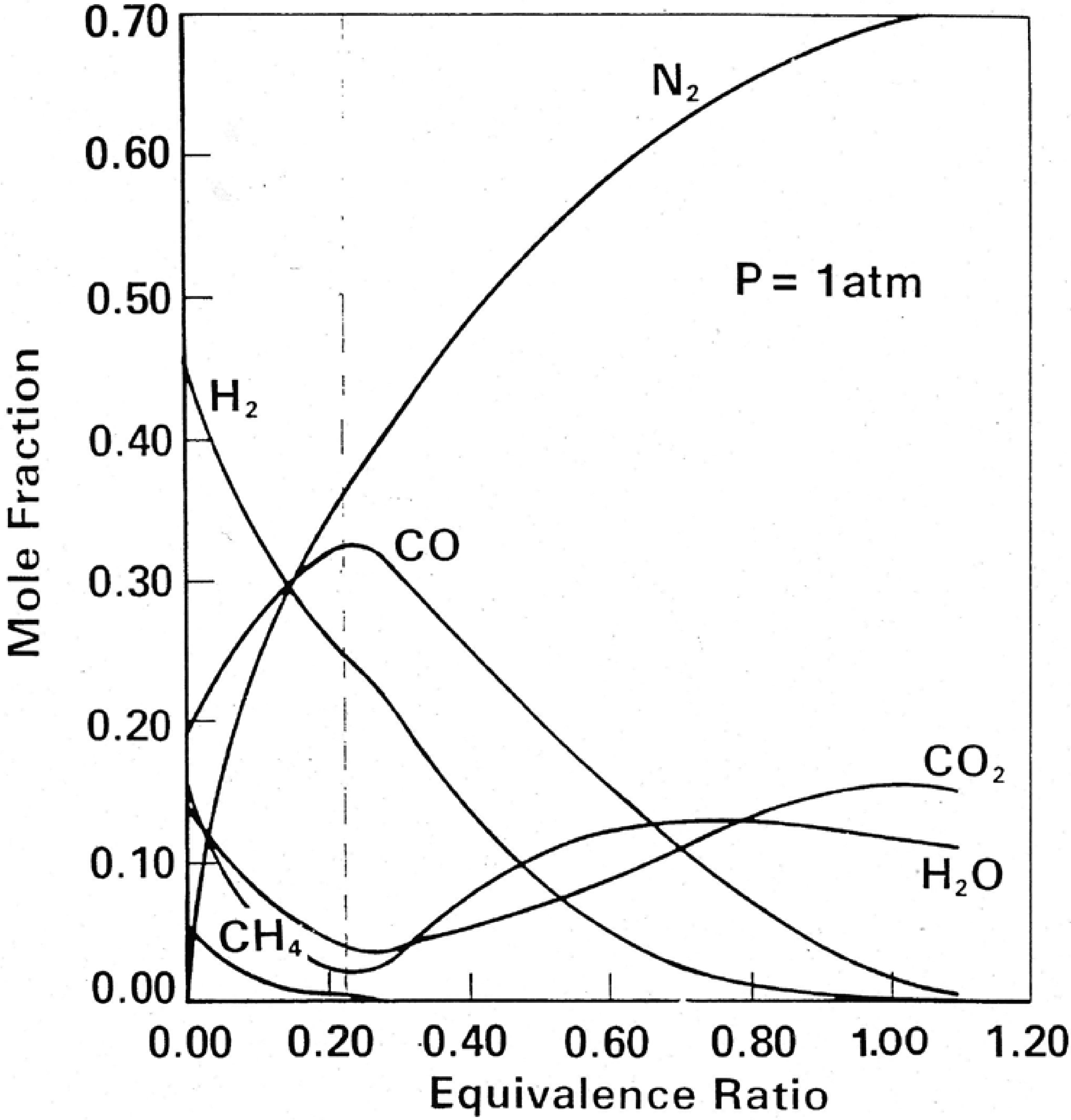


Figure S-3. Equilibrium Composition for Adiabatic Air/Biomass Reaction

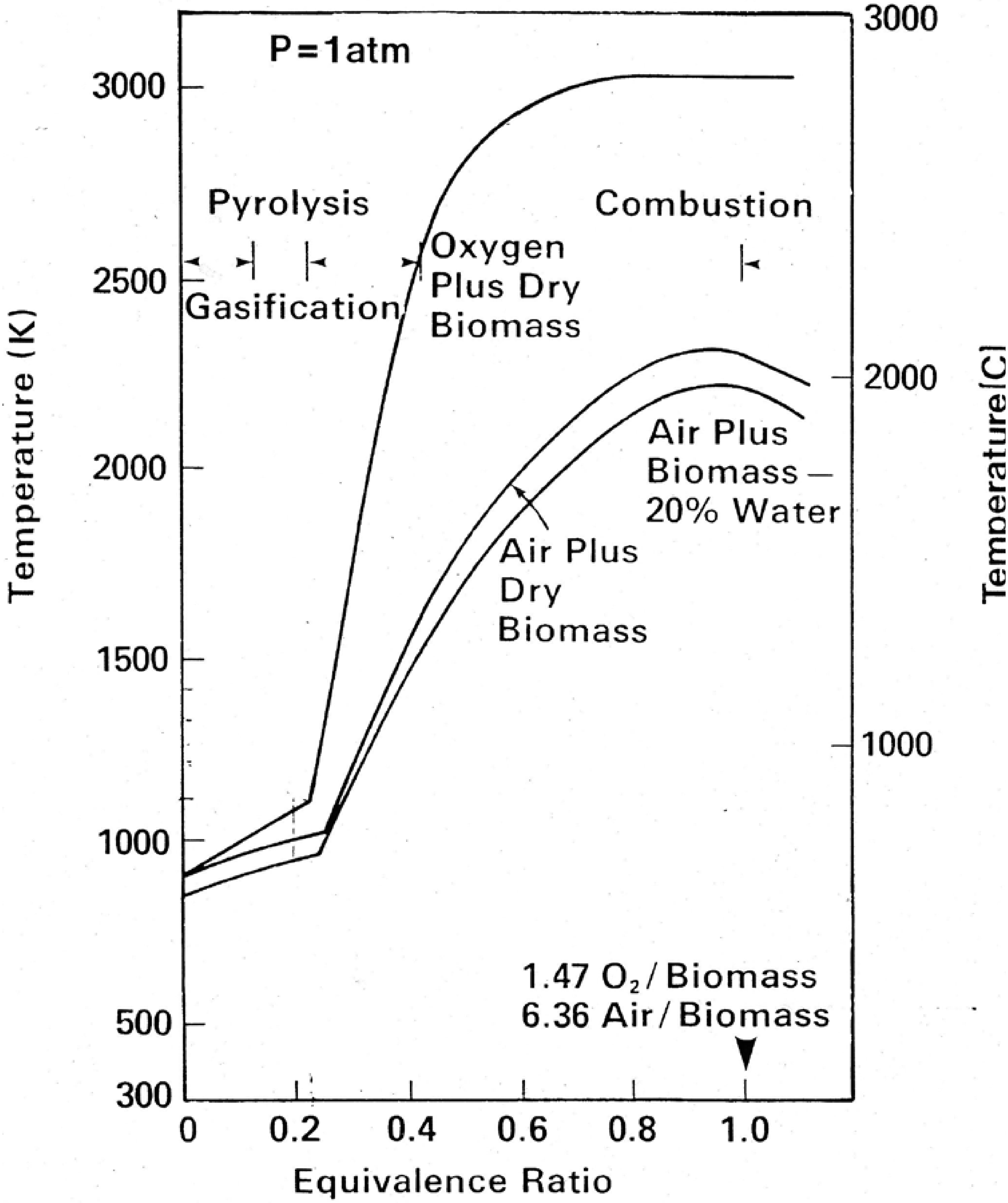


Figure S-2. Biomass Adiabatic Reaction Temperatures

Main Gasification Reactions

Combustion:

Carbon: $C + O_2 = CO_2 + 393.77$ kJ/mole
Hydrogen: $H_2 + \frac{1}{2} O_2 = H_2O + 742$ kJ/mole
Carbon Monoxide: $CO + \frac{1}{2} O_2 = CO_2 +$???
(add in other gasses, tars)

Reduction:

Boudouard Reaction: $CO_2 + C = 2CO - 172.58$ kJ/mole
Water Gas: $C + H_2O = CO + H_2 - 131.38$ kJ/mole

Shift Reactions:

Water Shift: $CO + H_2O = CO_2 + H_2 + 41.2$ vkJ/mole
Methanization: $C + 2H_2 = CH_4 + 74.9$ kJ/mole

Reaction Equilibrium: CO2 + C <==> 2CO

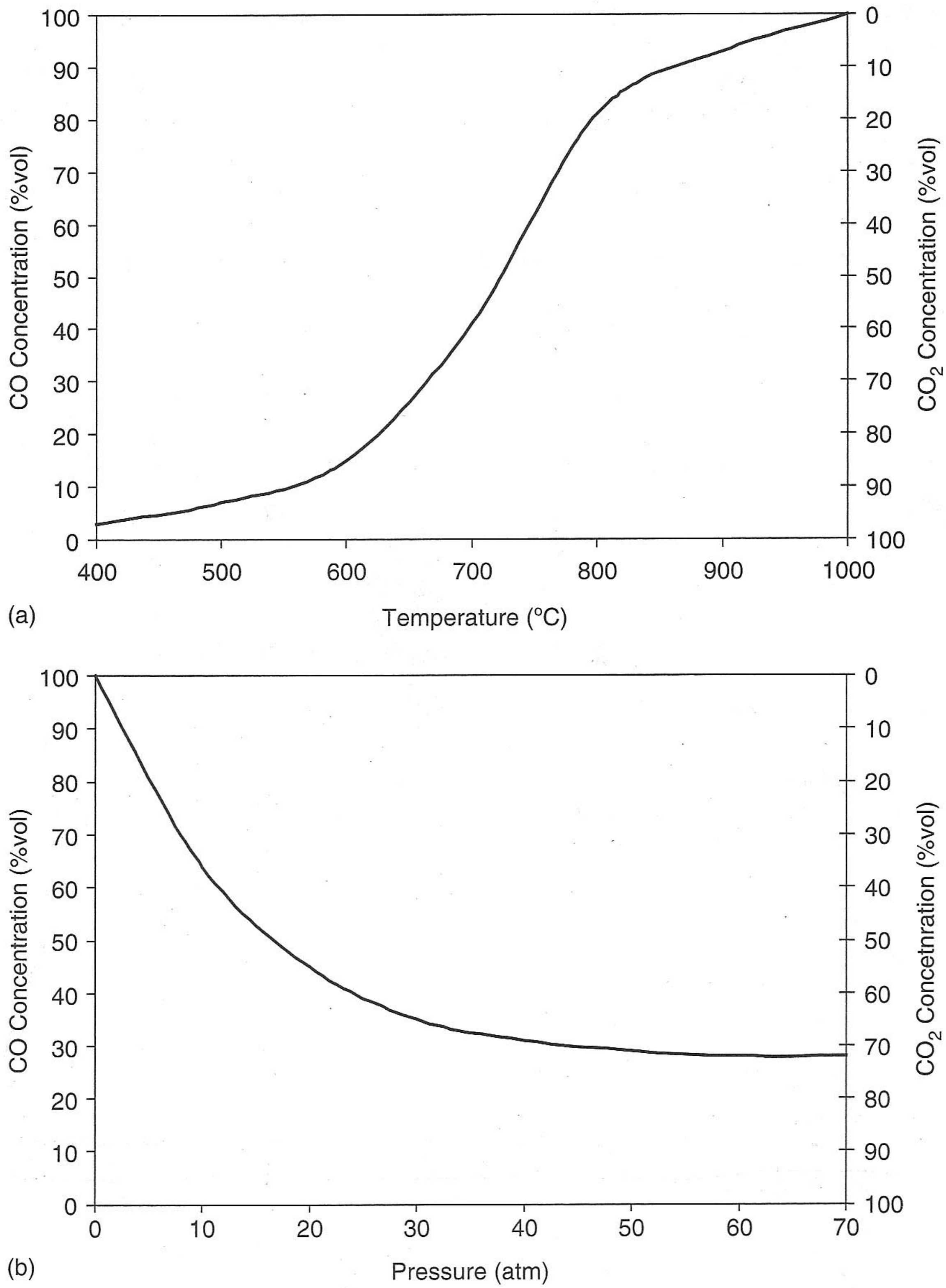


FIGURE 3.3 Boudouard reaction equilibrium: variation of carbon monoxide and carbon dioxide concentrations for gasification of carbon with oxygen (a) with temperature at a pressure of 1.0 atm, and (b) with pressure at a temperature of 800°C.

Source: Basu, Prabir. Combustion and Gasification in Fluidized Beds, pg 70, 2006.

Reaction Equilibrium: H2O + C <==> H2 + 2CO

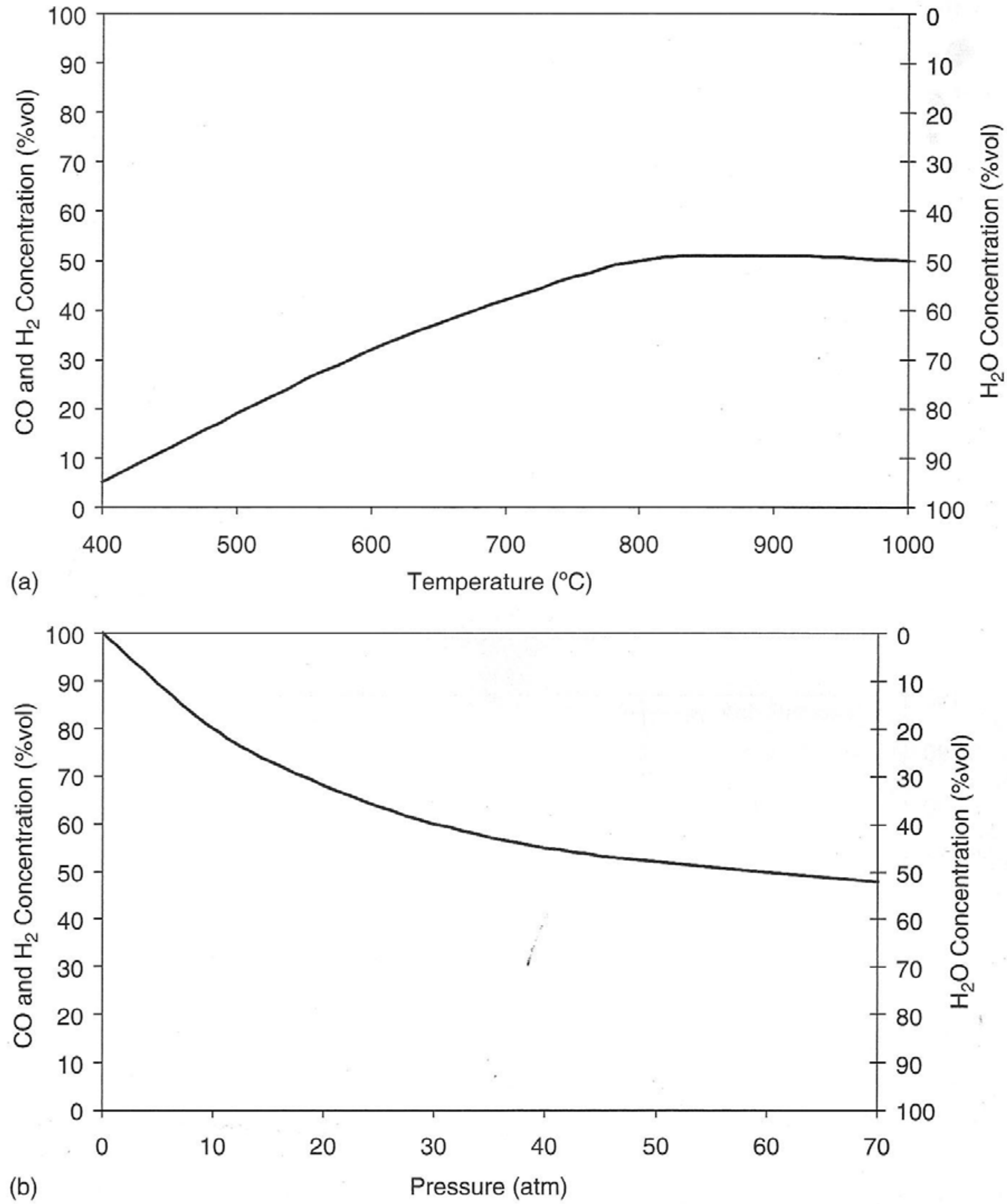


FIGURE 3.4 Water–gas reaction equilibrium: variation of carbon monoxide, hydrogen and steam (a) with temperature at a pressure of 1.0 atm, and (b) with pressure at a temperature of 800°C.

Source: Basu, Prabir. Combustion and Gasification in Fluidized Beds, pg 71. 2006

Reaction Equilibrium: C + H2 <==> CH4

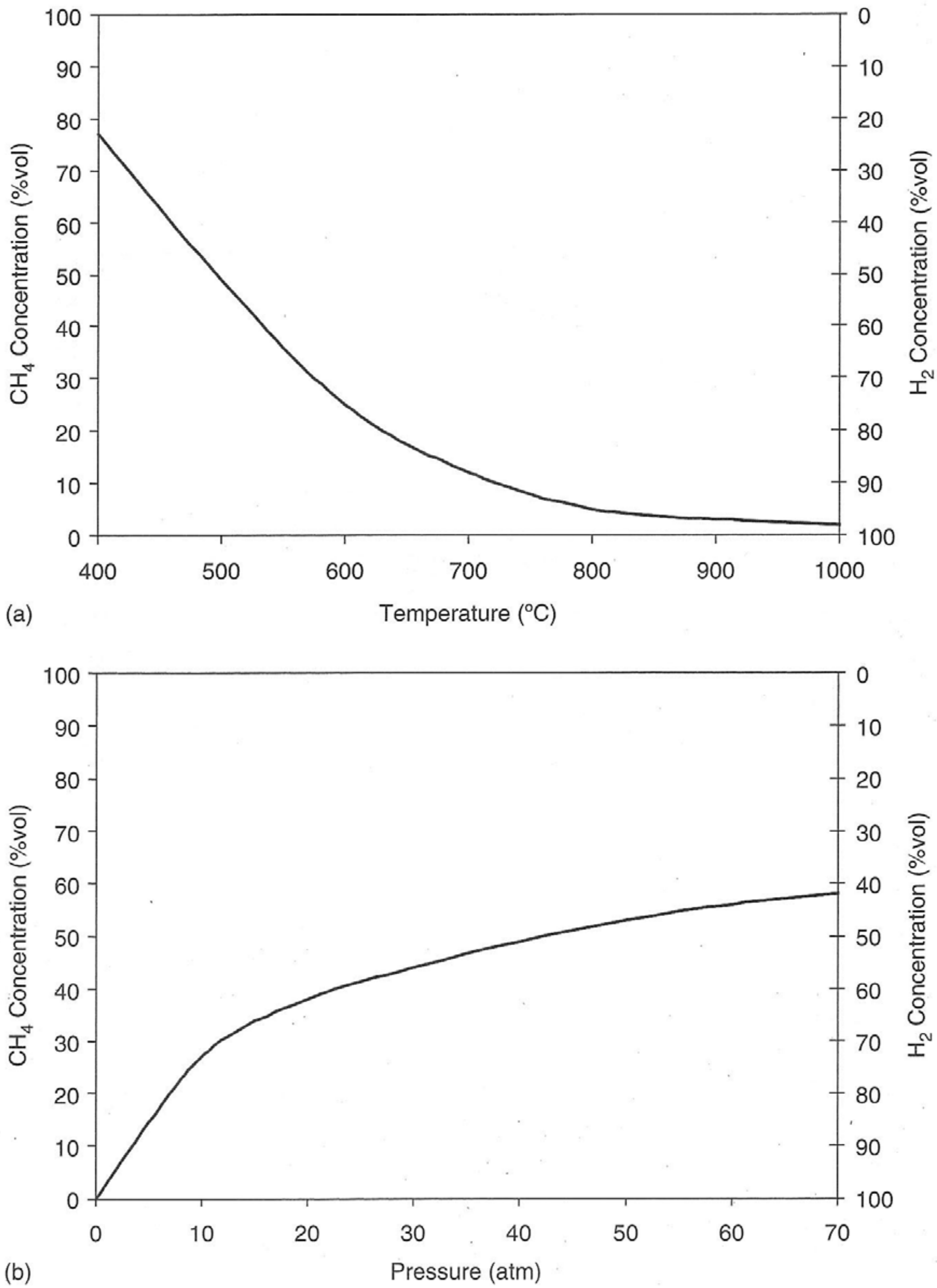
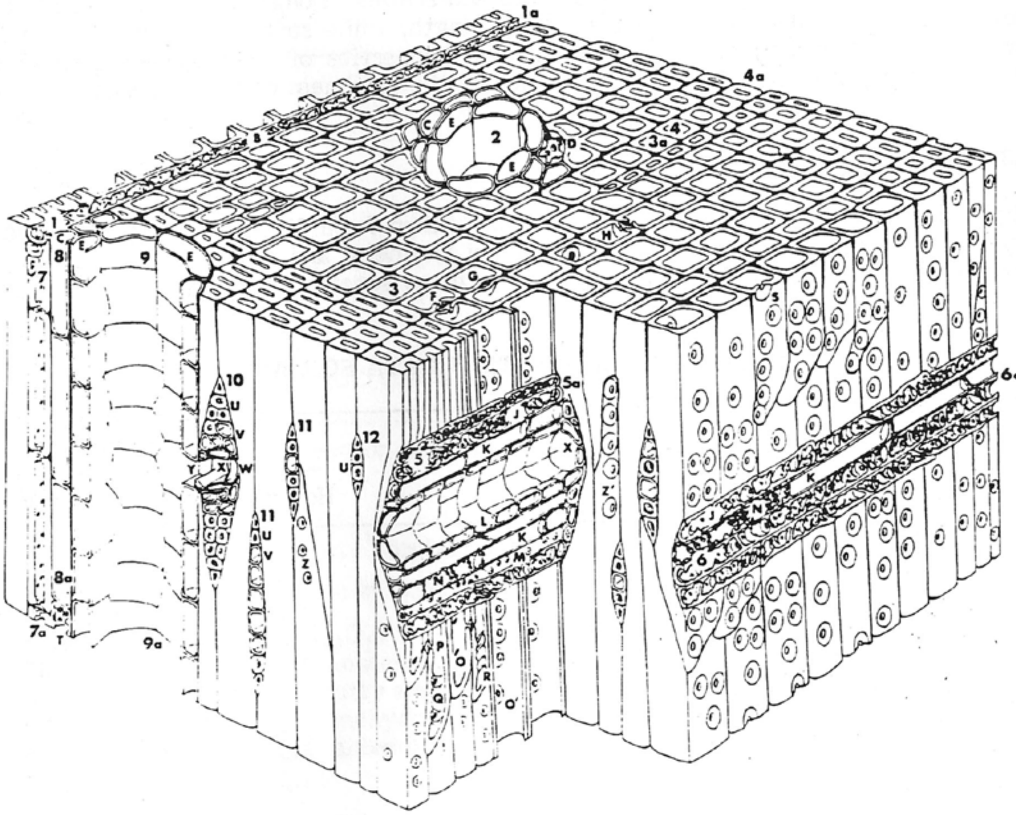
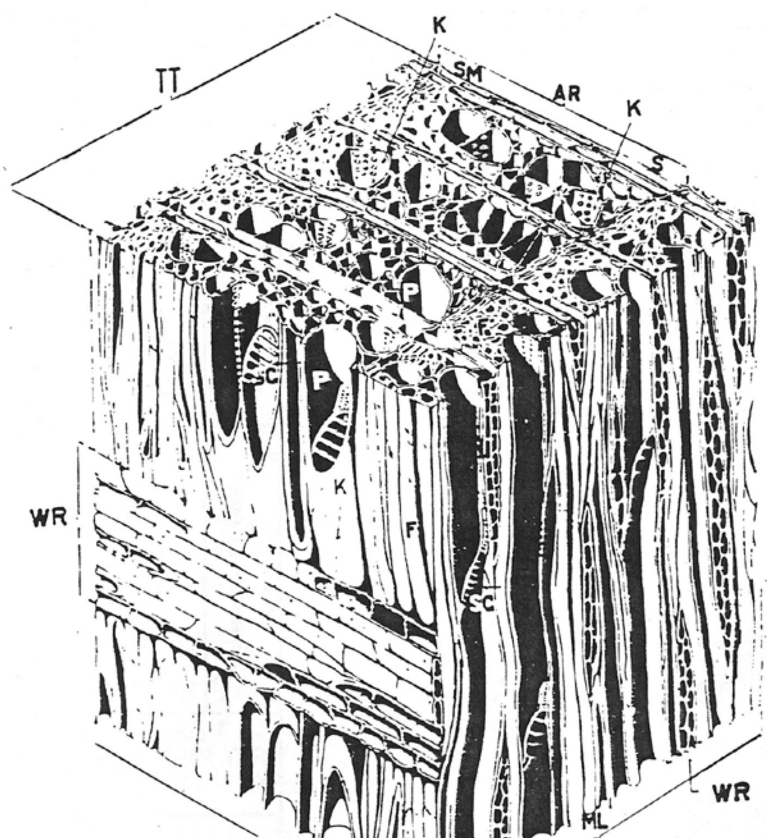


FIGURE 3.5 Variation of methane and hydrogen concentration at equilibrium (a) with temperature at a pressure of 1.0 atm, and (b) with pressure at a temperature of 800°C.

Source: Basu, Prabir. Combustion and Gasification in Fluidized Beds, pg 72. 2006

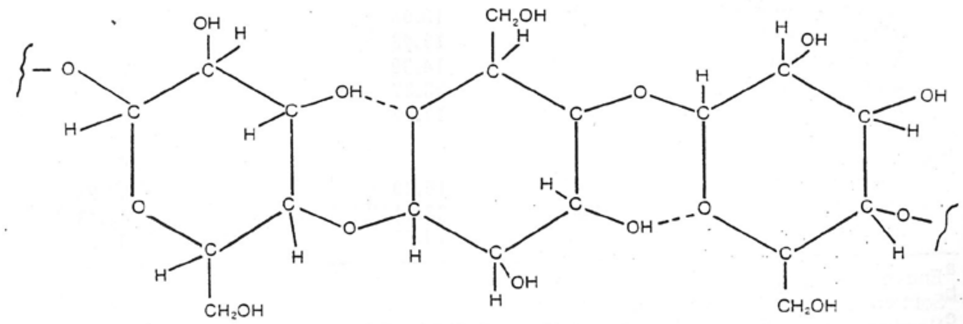


Gross Structure of a Typical Southern Pine Softwood

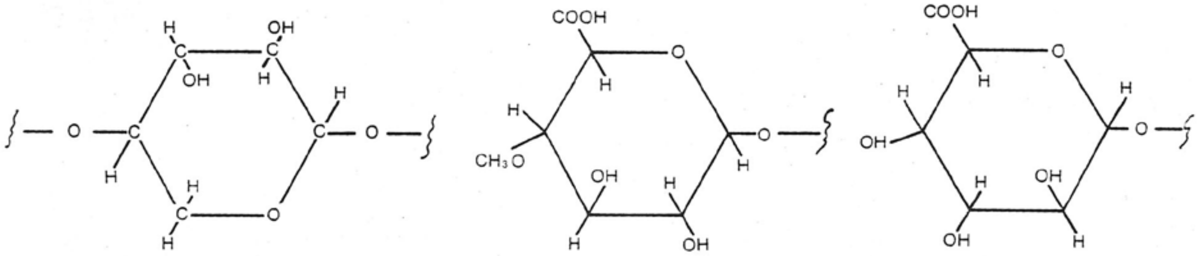


Gross Structure of a Typical Hardwood

Chemical Composition of Wood:
Cellulose, Hemicellulose, Lignin & Extractables



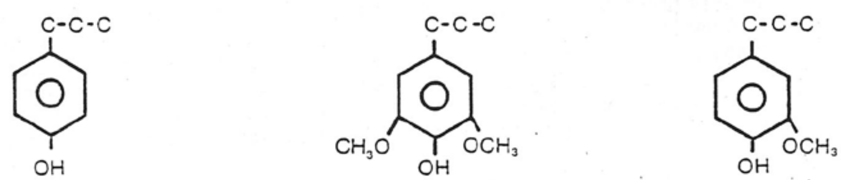
The Cellulose Molecule



Xylan

Acid Xylans-Terminal Groups

Xylan Hemicellulose Structures



p-hydroxylphenylpropane syringylpropane guaiacylpropane

Several Monomer Units in Lignin

EXTRACTABLE COMPONENTS OF WOOD

Volatile Oils (removed by steam or ether soluble)

- Terpenes ($C_{12}H_{16}$)
- Sesquiterpene ($C_{15}H_{24}$)
  and their oxygenated derivatives

Resins and Fatty Acids (soluble in ether)

- Resin acids ($C_{20}H_{30}O_2$)
- Fatty acids (oleic, linoleic, palmitic)
- Glyceryl esters of fatty acids
- Waxes (esters of monohydroxy alcohols and fatty acids)
- Phytosterols (high molecular weight cyclic alcohols)

Pigments (soluble in alcohol)

- Flavonols, Pyrones, Anthranols (multi-ring naphthenic and aromatic alcohols, chlorides, ketones acids)
- Tannins (amorphous polyhydroxylic phenols)

Carbohydrate Components (water soluble)

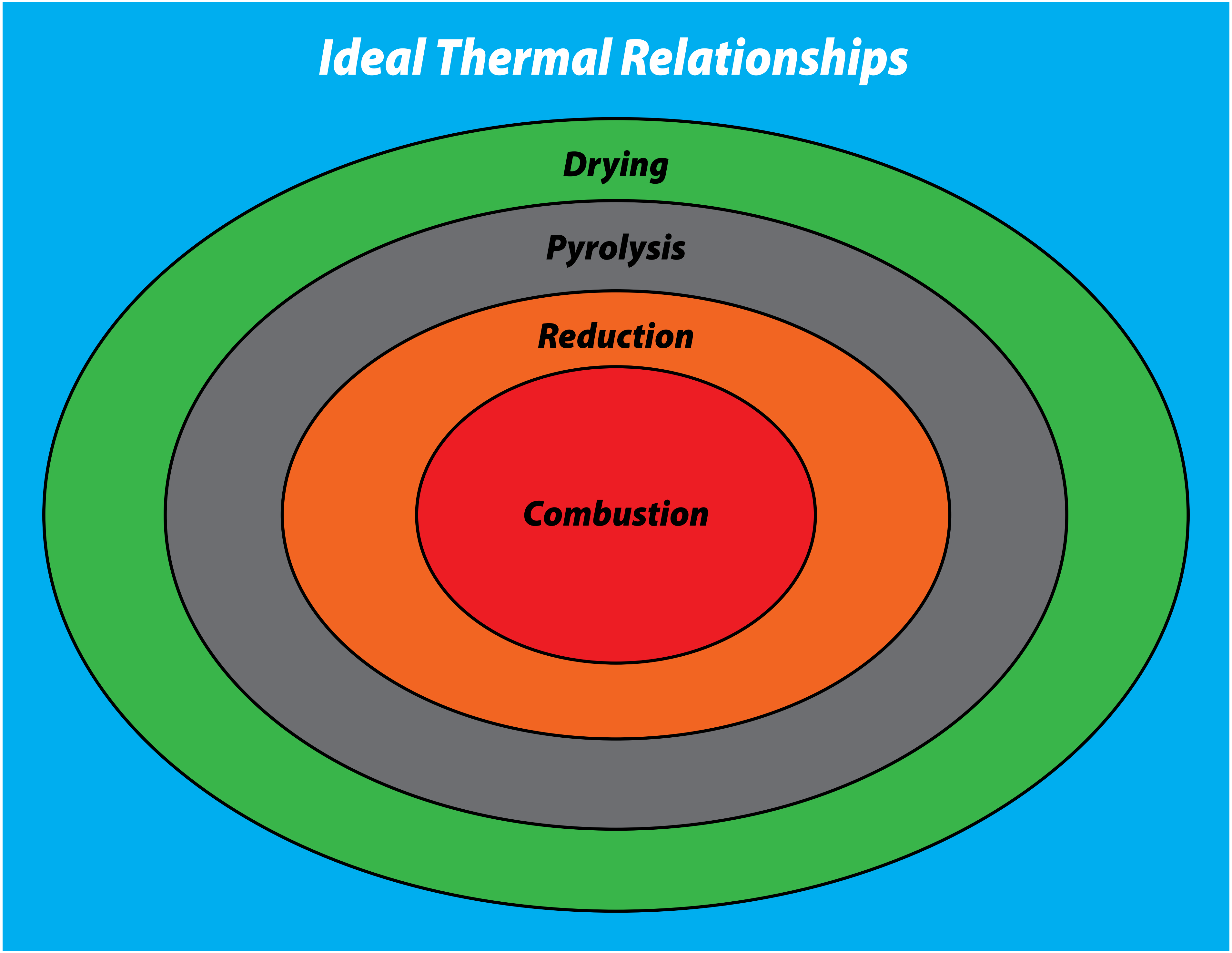
- Starch
- Simple sugars
- Organic acids

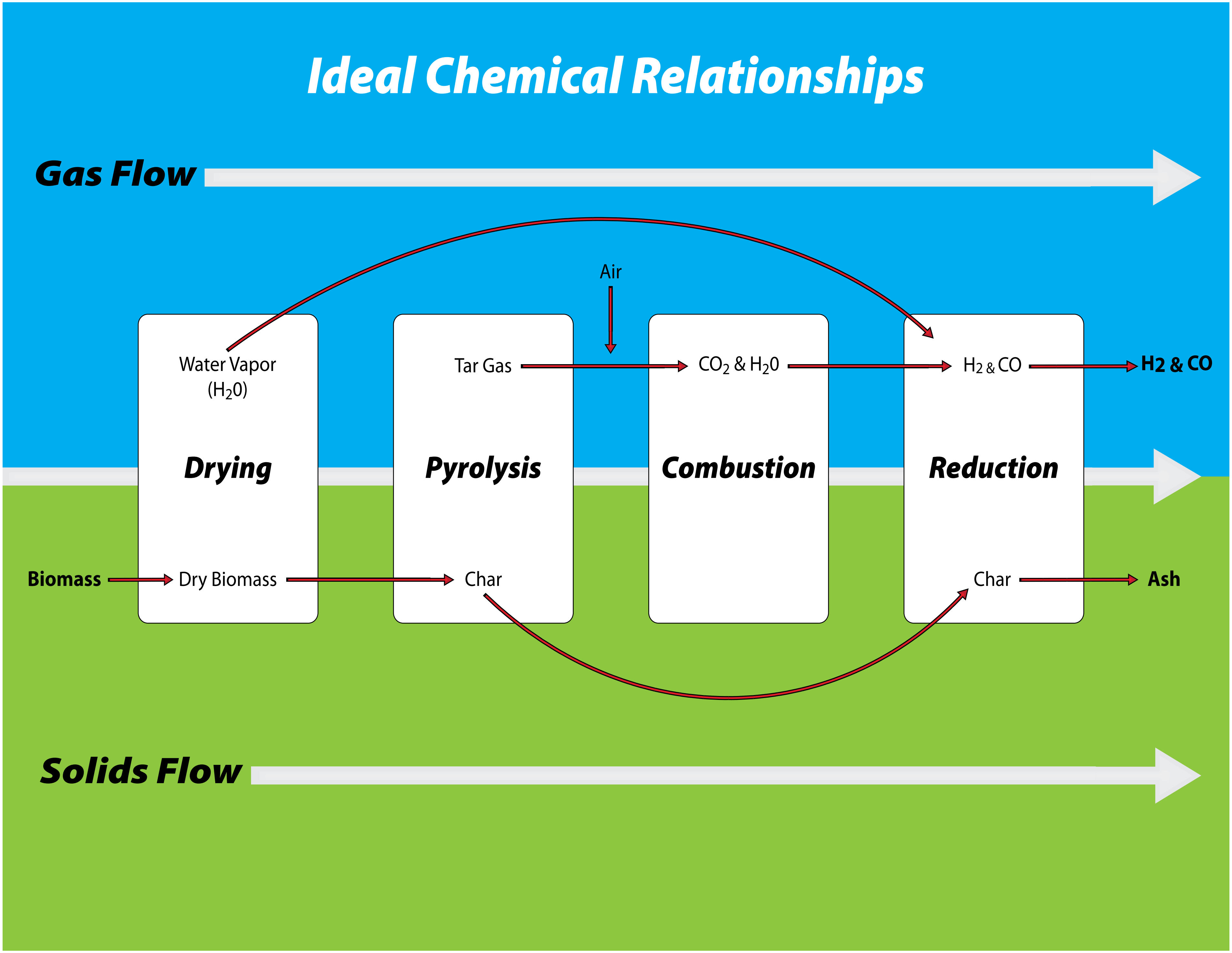
Table 3-3. **PROXIMATE ANALYSIS DATA FOR SELECTED SOLID FUELS AND BIOMASS MATERIALS**
(Dry Basis, Weight Percent)

	Volatile Matter (VM*)	Fixed Carbon (FC*)	Ash*	Reference
Coals				
Pittsburgh seam coal	33.9	55.8	10.3	Bituminous Coal Research 1974
Wyoming Elkol coal	44.4	51.4	4.2	Bituminous Coal Research 1974
Lignite	43.0	46.6	10.4	Bituminous Coal Research 1974
Oven Dry Woods				
Western hemlock	84.8	15.0	0.2	Howlett and Gamache 1977
Douglas fir	86.2	13.7	0.1	Howlett and Gamache 1977
White fir	84.4	15.1	0.5	Howlett and Gamache 1977
Ponderosa pine	87.0	12.8	0.2	Howlett and Gamache 1977
Redwood	83.5	16.1	0.4	Howlett and Gamache 1977
Cedar	77.0	21.0	2.0	Howlett and Gamache 1977
Oven Dry Barks				
Western hemlock	74.3	24.0	1.7	Howlett and Gamache 1977
Douglas fir	70.6	27.2	2.2	Howlett and Gamache 1977
White fir	73.4	24.0	2.6	Howlett and Gamache 1977
Ponderosa pine	73.4	25.9	0.7	Howlett and Gamache 1977
Redwood	71.3	27.9	0.8	Howlett and Gamache 1977
Cedar	86.7	13.1	0.2	Howlett and Gamache 1977
Mill Woodwaste Samples				
-4 Mesh redwood shavings	76.2	23.5	0.3	Boley and Landers 1969
-4 Mesh Alabama oakchips	74.7	21.9	3.3	Boley and Landers 1969
Municipal Refuse and Major Components				
National average waste	65.9	9.1	25.0	Klass and Ghosh 1973
Newspaper (9.4% of average waste)	86.3	12.2	1.5	Klass and Ghosh 1973
Paper boxes (23.4%)	81.7	12.9	5.4	Klass and Ghosh 1973
Magazine paper (6.8%)	69.2	7.3	23.4	Klass and Ghosh 1973
Brown paper (5.6%)	89.1	9.8	1.1	Klass and Ghosh 1973
Pyrolysis Chars				
Redwood (790 F to 1020 F)	30.0	67.7	2.3	Howlett and Gamache 1977
Redwood (800 F to 1725 F)	23.9	72.0	4.1	Howlett and Gamache 1977
Oak (820 F to 1185 F)	25.3	59.3	14.9	Howlett and Gamache 1977
Oak (1060 F)	27.1	55.6	17.3	Howlett and Gamache 1977

Table 3-4. ULTIMATE ANALYSIS DATA FOR SELECTED SOLID FUELS AND BIOMASS MATERIALS
(Dry Basis, Weight Percent)

Material	C	H	N	S	O	Ash	Higher Heating Value (Btu/lb)	Reference
Pittsburgh seam coal	75.5	5.0	1.2	3.1	4.9	10.3	13,650	Tillman 1978
West Kentucky No. 11 coal	74.4	5.1	1.5	3.8	7.9	7.3	13,460	Bituminous Coal Research 1974
Utah coal	77.9	6.0	1.5	0.6	9.9	4.1	14,170	Tillman 1978
Wyoming Elkol coal	71.5	5.3	1.2	0.9	16.9	4.2	12,710	Bituminous Coal Research 1974
Lignite	64.0	4.2	0.9	1.3	19.2	10.4	10,712	Bituminous Coal Research 1974
Charcoal	80.3	3.1	0.2	0.0	11.3	3.4	13,370	Tillman 1978
Douglas fir	52.3	6.3	0.1	0.0	40.5	0.8	9,050	Tillman 1978
Douglas fir bark	56.2	5.9	0.0	0.0	36.7	1.2	9,500	Tillman 1978
Pine bark	52.3	5.8	0.2	0.0	38.8	2.9	8,780	Tillman 1978
Western hemlock	50.4	5.8	0.1	0.1	41.4	2.2	8,620	Tillman 1978
Redwood	53.5	5.9	0.1	0.0	40.3	0.2	9,040	Tillman 1978
Beech	51.6	6.3	0.0	0.0	41.5	0.6	8,760	Tillman 1978
Hickory	49.7	6.5	0.0	0.0	43.1	0.7	8,670	Tillman 1978
Maple	50.6	6.0	0.3	0.00	41.7	1.4	8,580	Tillman 1978
Poplar	51.6	6.3	0.0	0.0	41.5	0.6	8,920	Tillman 1978
Rice hulls	38.5	5.7	0.5	0.0	39.8	15.5	6,610	Tillman 1978
Rice straw	39.2	5.1	0.6	0.1	35.8	19.2	6,540	Tillman 1978
Sawdust pellets	47.2	6.5	0.0	0.0	45.4	1.0	8,814	Wen et al. 1974
Paper	43.4	5.8	0.3	0.2	44.3	6.0	7,572	Bowerman 1969
Redwood wastewood	53.4	6.0	0.1	39.9	0.1	0.6	9,163	Boley and Landers 1969
Alabama oak woodwaste	49.5	5.7	0.2	0.0	41.3	3.3	8,266	Boley and Landers 1969
Animal waste	42.7	5.5	2.4	0.3	31.3	17.8	7,380	Tillman 1978
Municipal solid waste	47.6	6.0	1.2	0.3	32.9	12.0	8,546	Sanner et al. 1970


Ideal Thermal Relationships
Drying
Pyrolysis
Reduction
Combustion


Ideal Chemical Relationships
Gas Flow
Air
Water Vapor
(H_2O)
Tar Gas
CO_2 & H_2O
H_2 & CO
H2 & CO
Drying
Pyrolysis
Combustion
Reduction
Biomass
Dry Biomass
Char
Char
Ash
Solids Flow