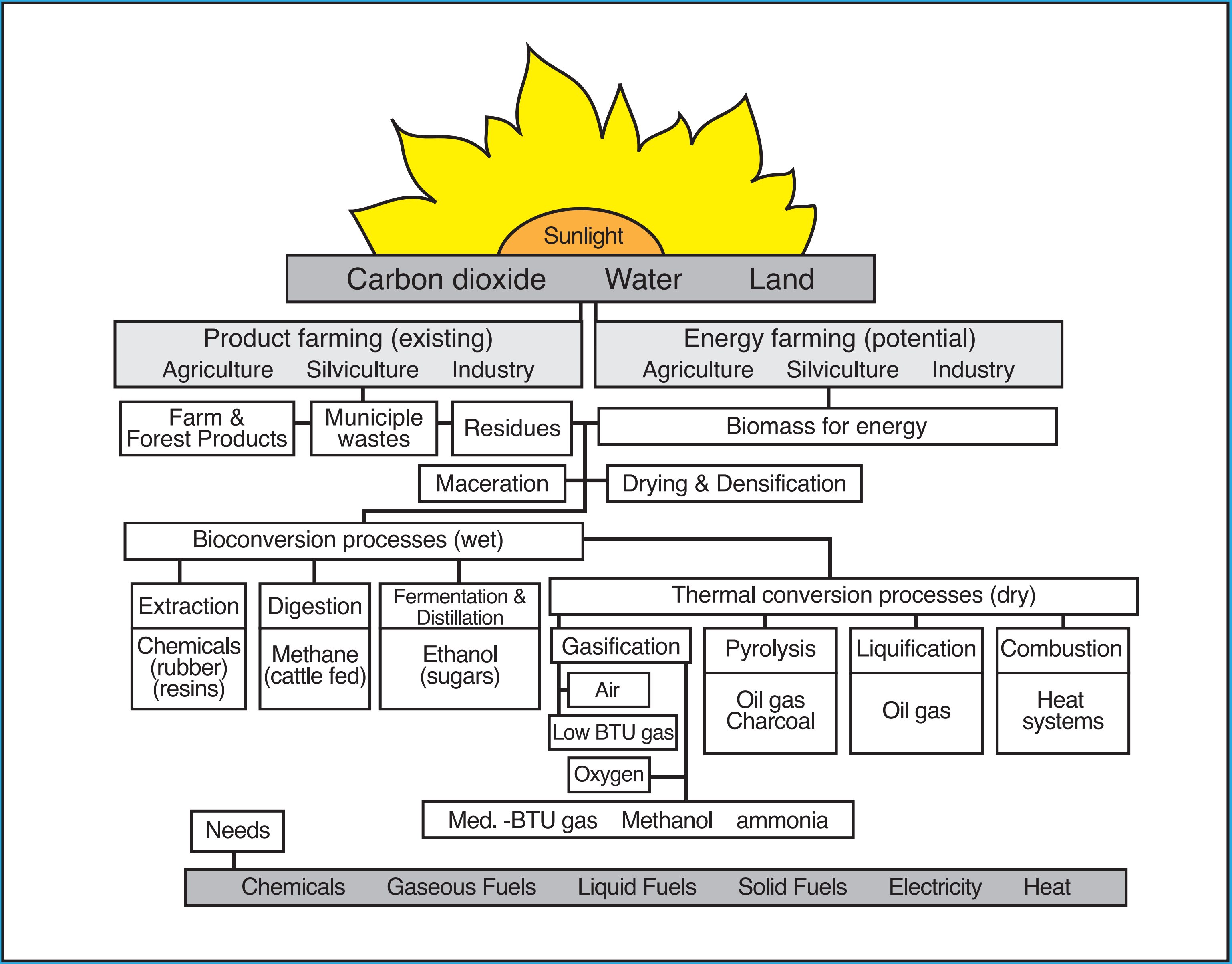
Pathways of Biomass Energy



Sunlight

Carbon dioxide Water Land

Product farming (existing)
Agriculture Silviculture Industry

Energy farming (potential)
Agriculture Silviculture Industry

Farm & Forest Products

Municiple wastes

Residues

Biomass for energy

Maceration

Drying & Densification

Bioconversion processes (wet)

Extraction
Chemicals (rubber) (resins)

Digestion
Methane (cattle fed)

Fermentation & Distillation
Ethanol (sugars)

Thermal conversion processes (dry)

Gasification
Air
Low BTU gas
Oxygen

Pyrolysis
Oil gas Charcoal

Liquification
Oil gas

Combustion
Heat systems

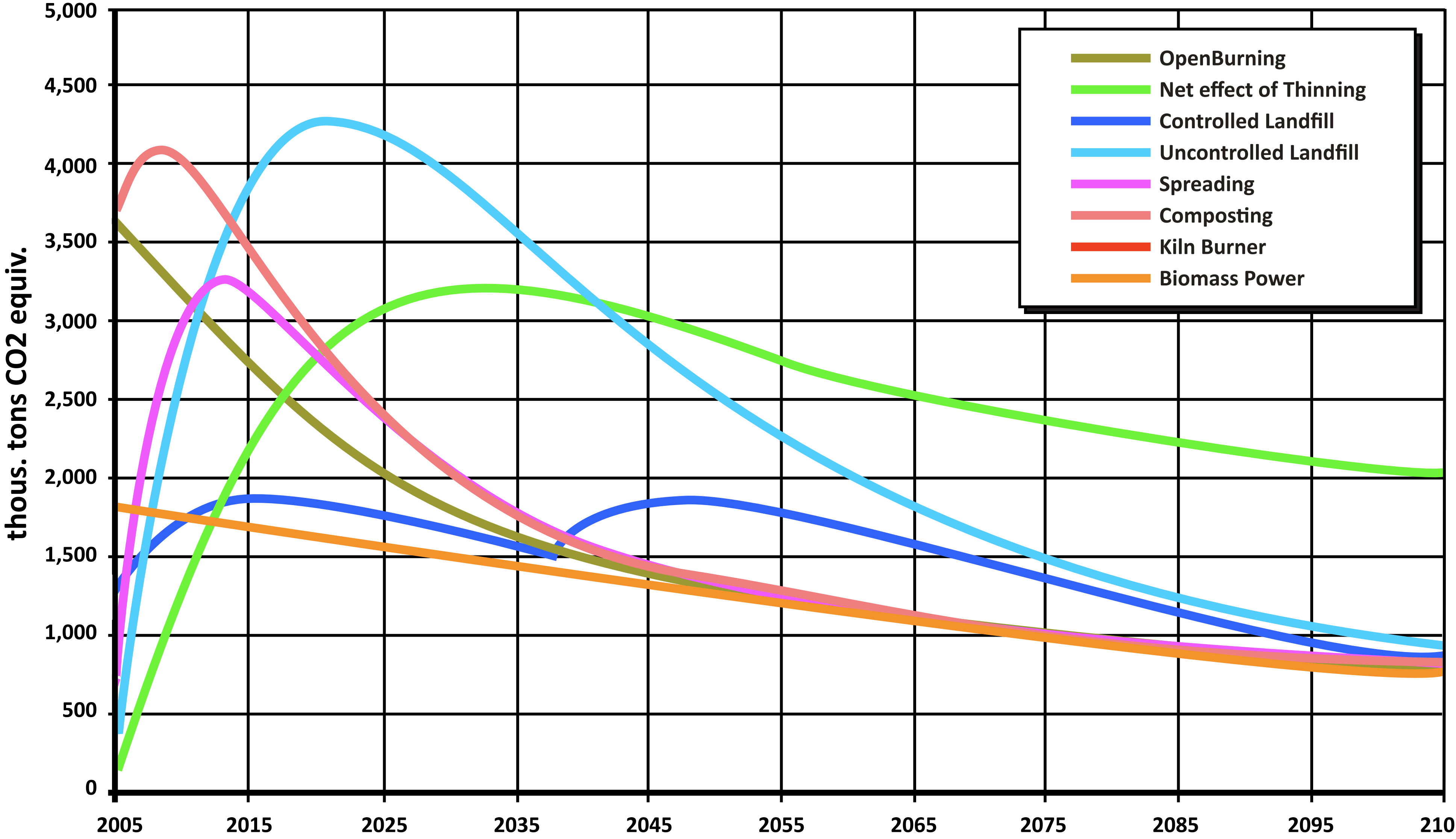
Med. -BTU gas Methanol ammonia

Needs

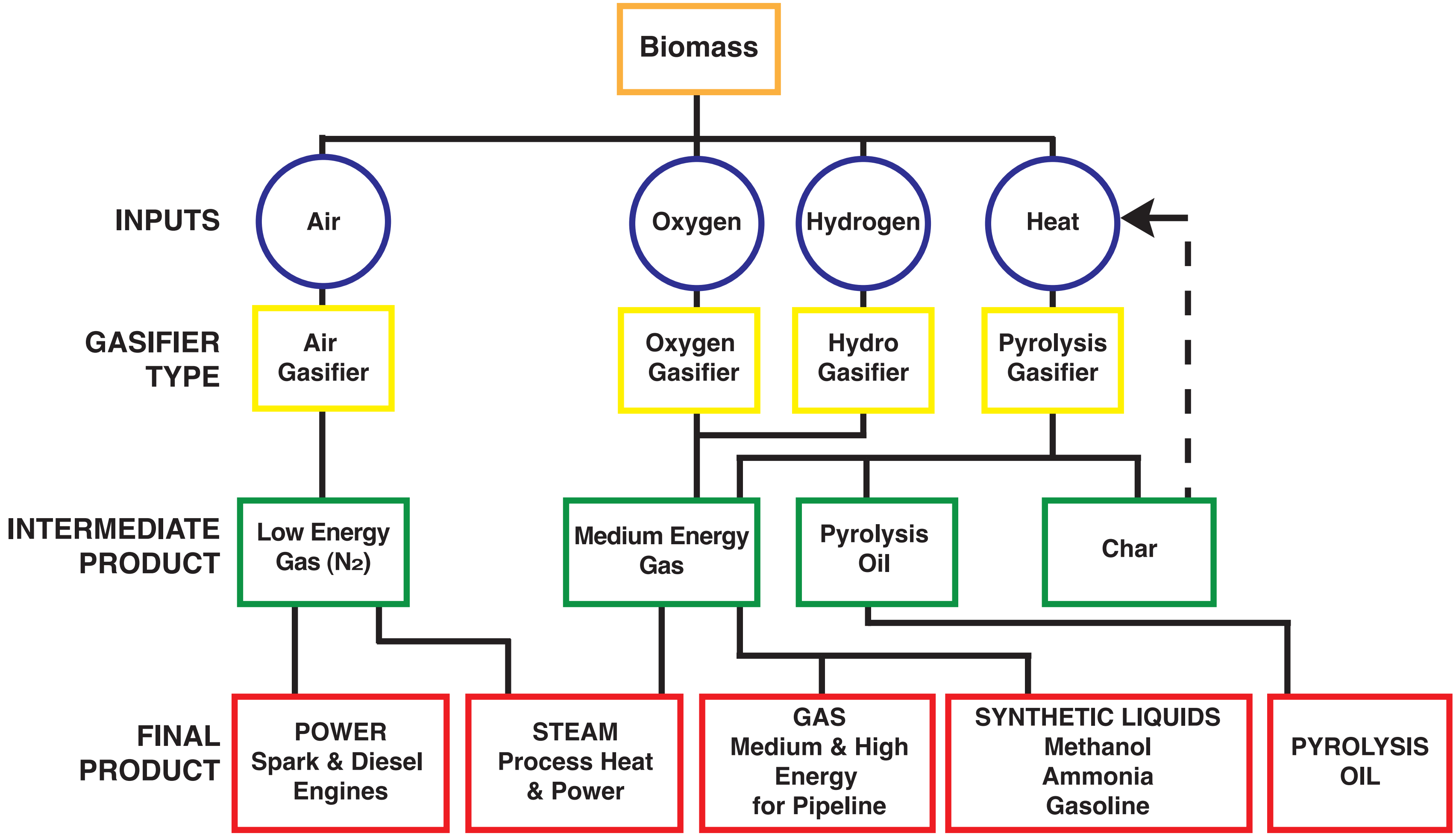
Chemicals Gaseous Fuels Liquid Fuels Solid Fuels Electricity Heat

Source: Tom Reed 1978

GHG Burden associated with the Disposal of 1 million BDT of Biomass



Pathways of Biomass Thermal Conversion



Biomass

INPUTS
Air
Oxygen
Hydrogen
Heat

GASIFIER TYPE
Air Gasifier
Oxygen Gasifier
Hydro Gasifier
Pyrolysis Gasifier

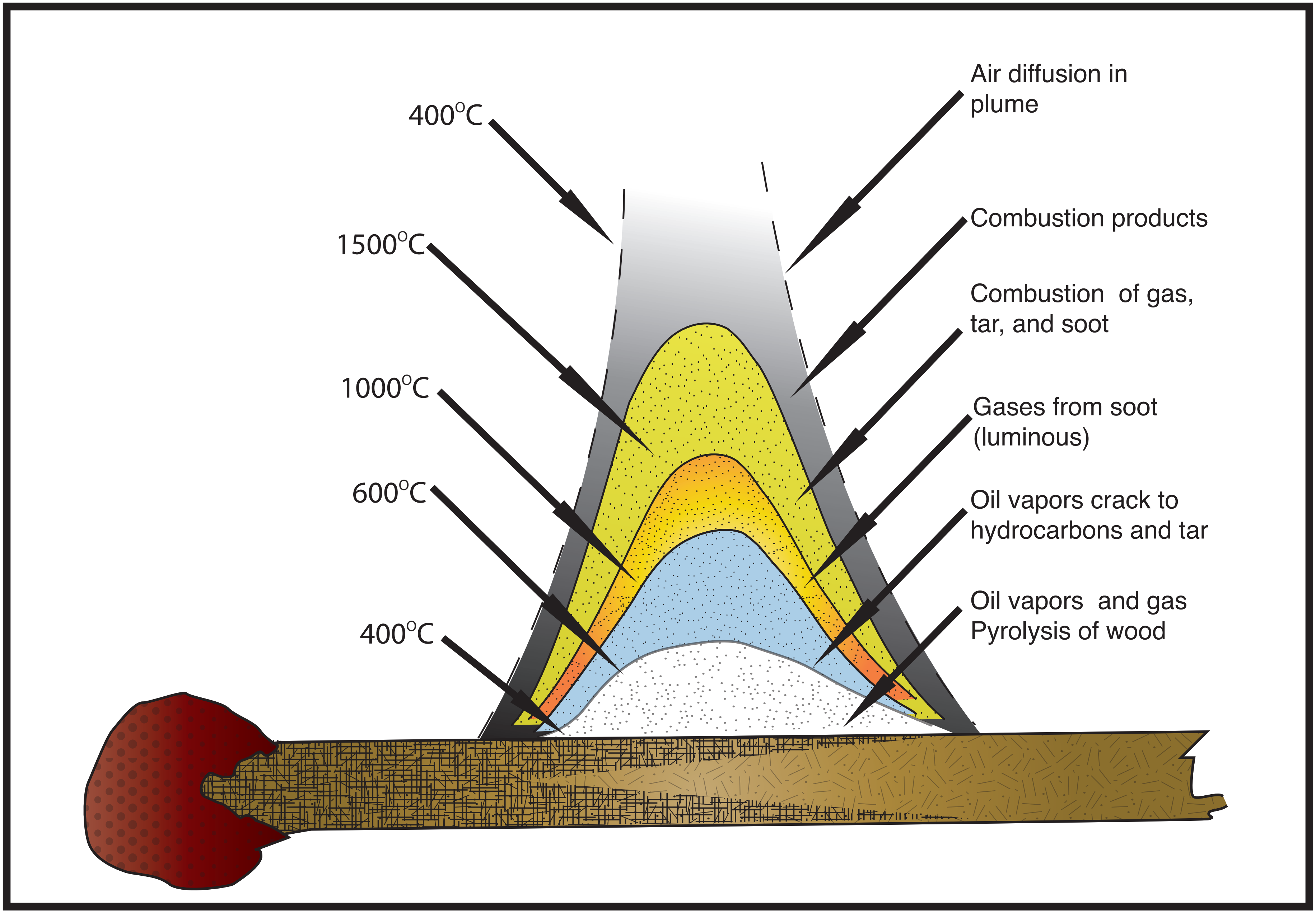
INTERMEDIATE PRODUCT
Low Energy Gas (N_2)
Medium Energy Gas
Pyrolysis Oil
Char

FINAL PRODUCT
POWER Spark & Diesel Engines
STEAM Process Heat & Power
GAS Medium & High Energy for Pipeline
SYNTHETIC LIQUIDS Methanol Ammonia Gasoline
PYROLYSIS OIL

Gasification Processes and Their Products

Adapted from Tom Reed

Pyrolysis, Gasification and Combustion in a Flaming Match



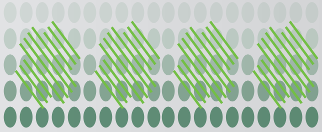
Adapted from Tom Reed

4 Processes in Gasification

not necessarily in order

Drying

heat →

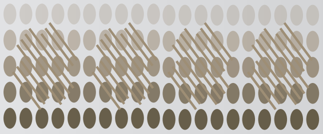


biomass (C H O)*

→ H2O

Pyrolysis

heat no air →



biomass (C H O)*

→ Charcoal and Tar

Combustion

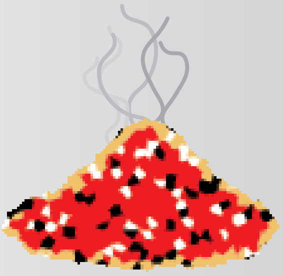
O_2/air →

tarry gas or charcoal

→ H_2O and CO_2

Reduction

CO_2 and H_2O →



hot charcoal (C)

→ H_2 and CO

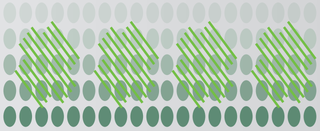
* Biomass is a combination of C, H, and O ($C\ H_{1.4}O_{0.6}$)

5 Processes in Gasification

The missing link

Drying

heat →

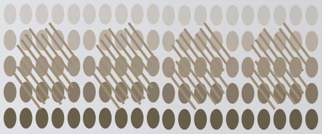


biomass (C H O)*

→ H2O

Pyrolysis

heat no air →



biomass (C H O)*

→ Charcoal and Tar

Combustion

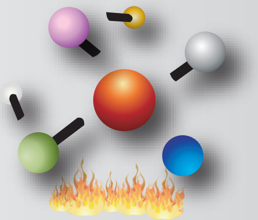
O_2/air →

tarry gas or charcoal

→ H_2O and CO_2

Cracking

Tarry Gas
Heavy Hydrocarbons →



Heat

→ H_2 and CO

Reduction

CO_2 and H_2O →

hot charcoal (C)

→ H_2 and CO

* Biomass is a combination of C, H, and O ($C\ H_{1.4}O_{0.6}$)

Temperature and Yield Profile for Biomass Pyrolysis

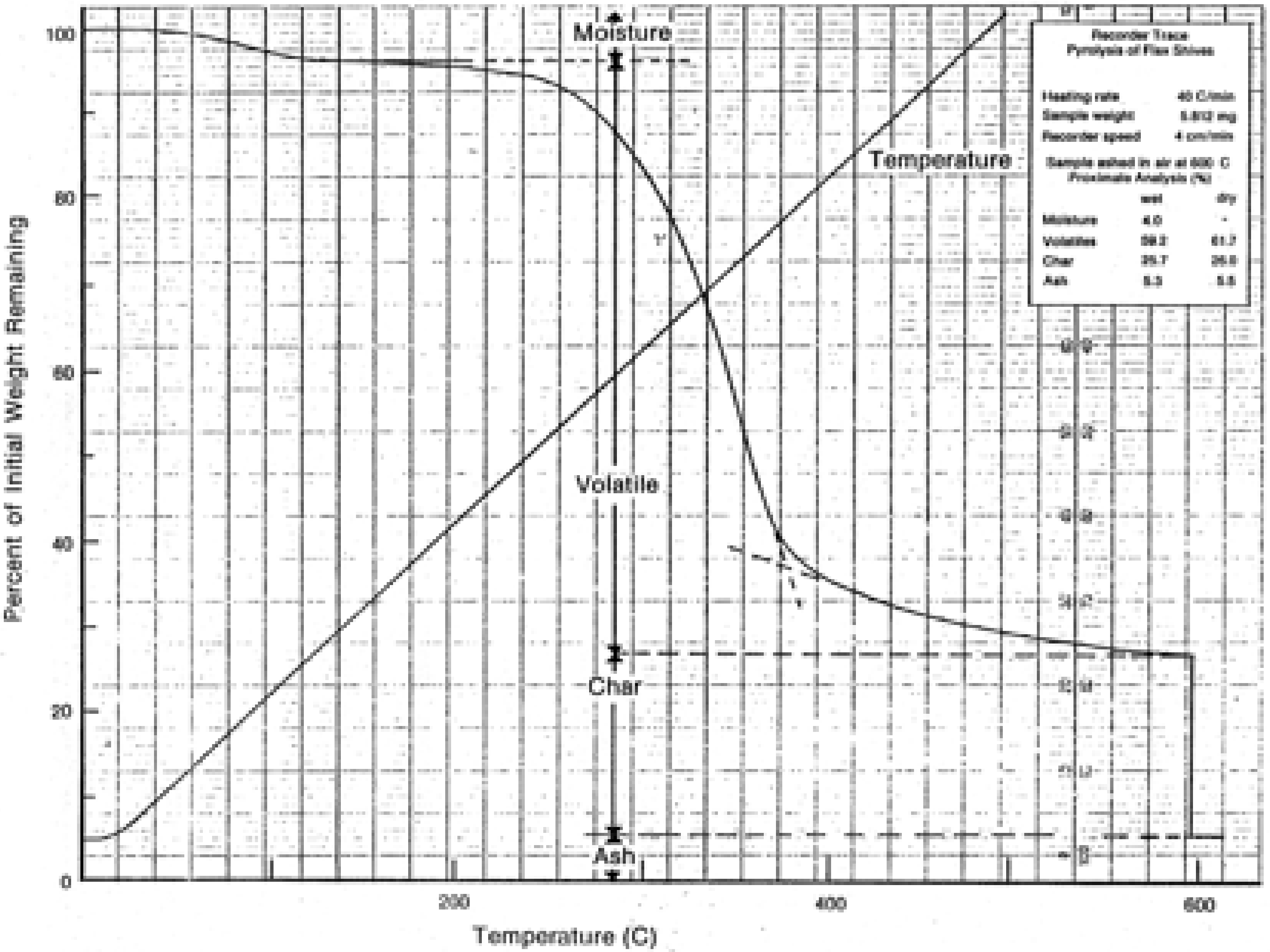


Figure 5-2. A Typical Dynamic TGA Result Obtained with Flax Shives and Showing Moisture, Volatile Matter, Char, and Ash Content

Source: T. Milne 1979

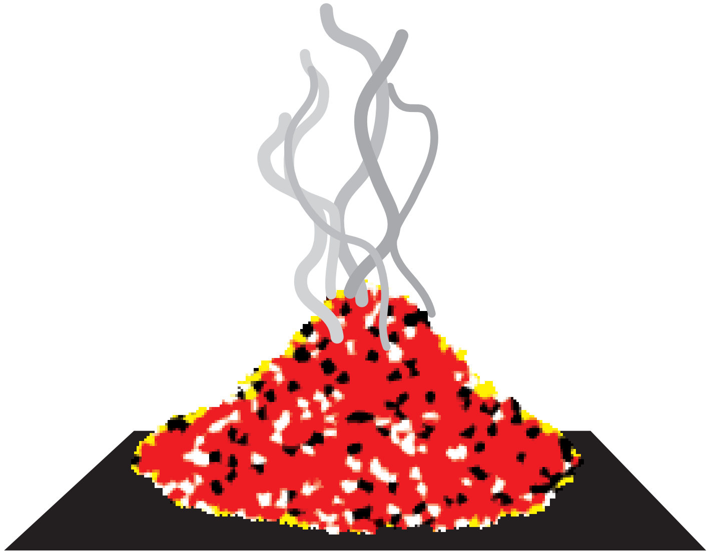
The Reduction Reactions

The Heart of Gasification

INPUT

CO_2 + H_2O
carbon dioxide + water vapor

C
carbon



Red Hot Charcoal Bed

OUTPUT

H_2 + CO
hydrogen + carbon monoxide

REACTIONS

$$CO_2 + C = 2CO$$

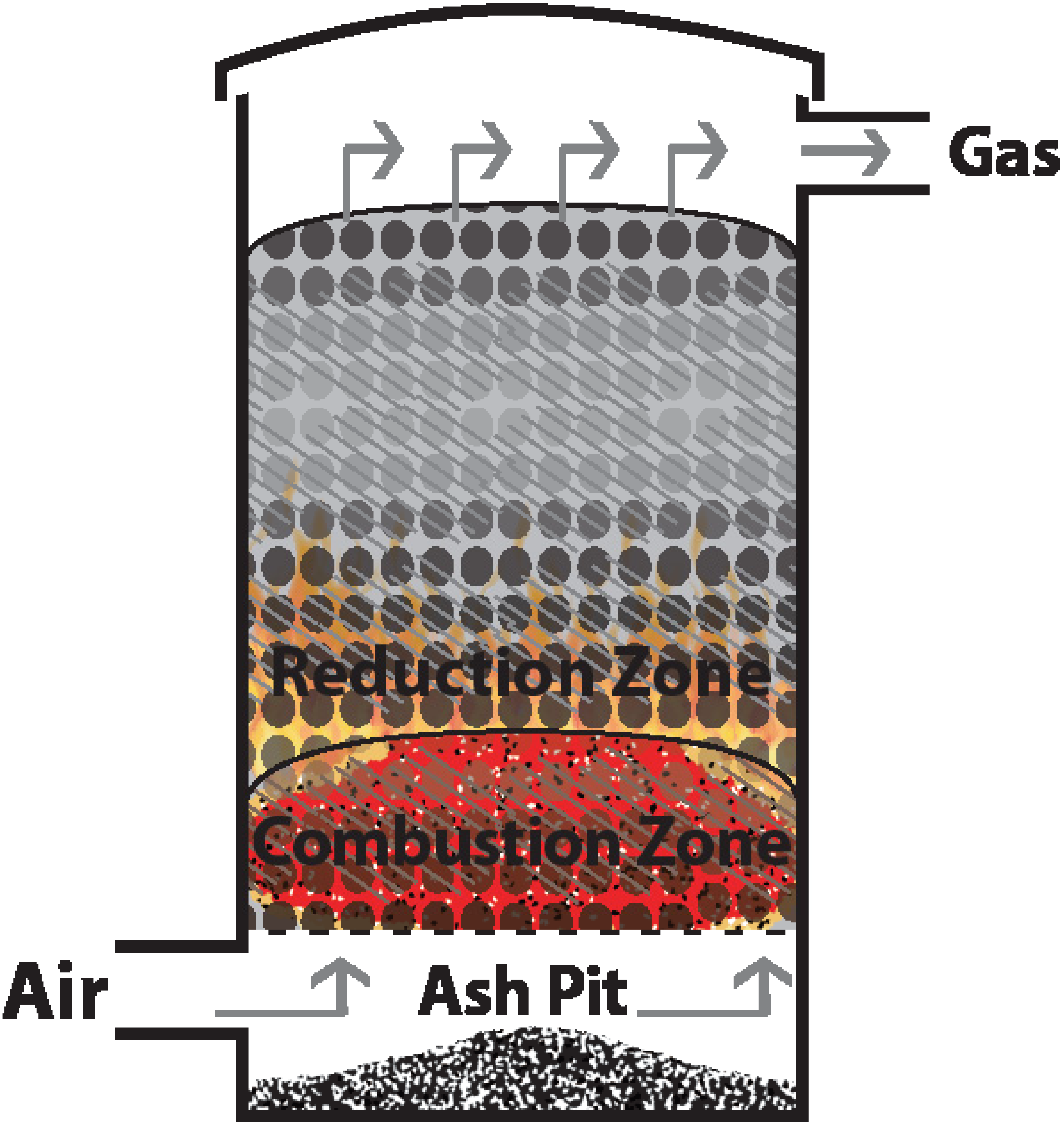
carbon dioxide + carbon = carbon monoxide

$$H_2O + C = H_2 + CO$$

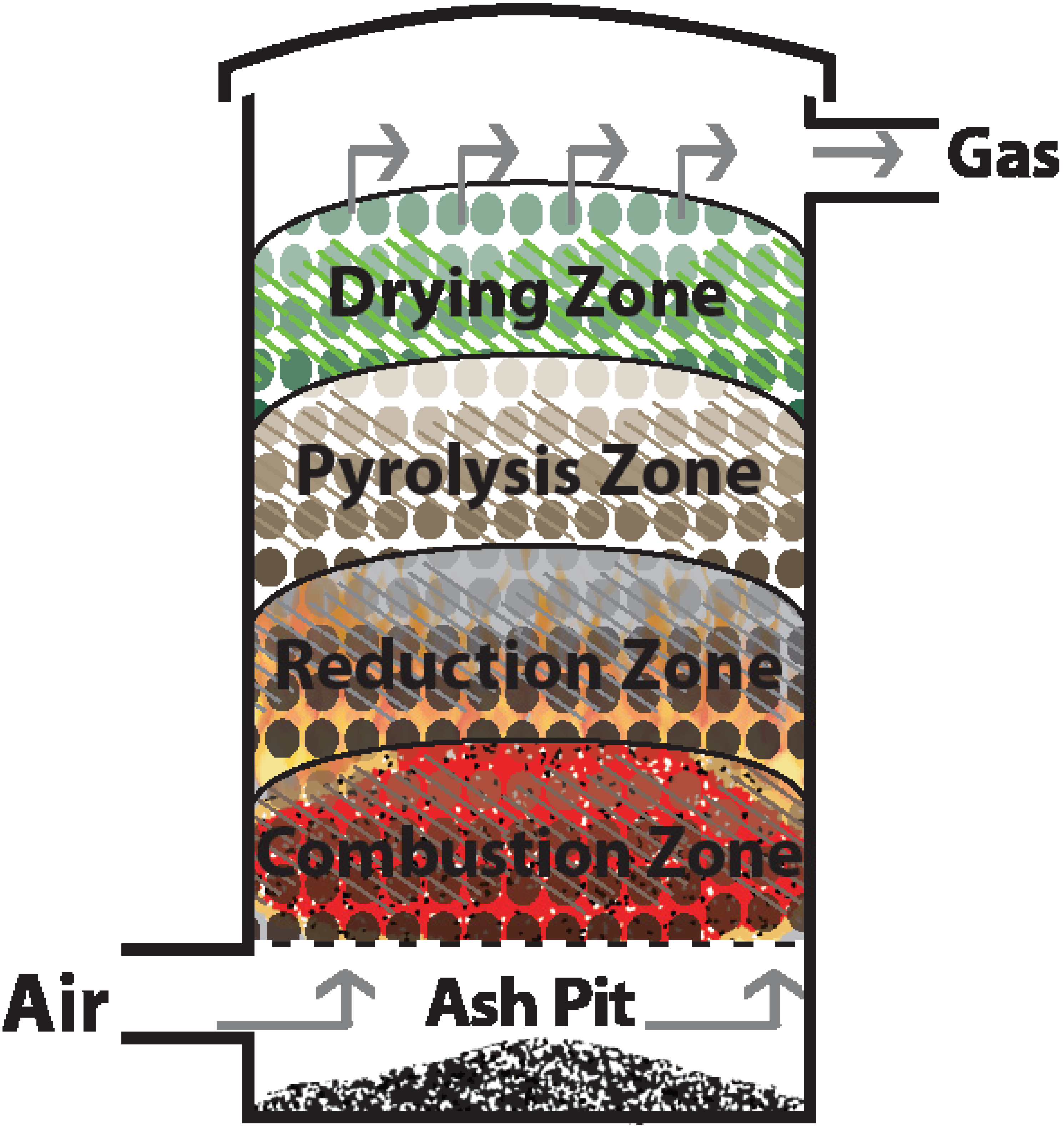
water vapor + carbon = hydrogen + carbon monoxide

Updraft Gasifier

Charcoal Only

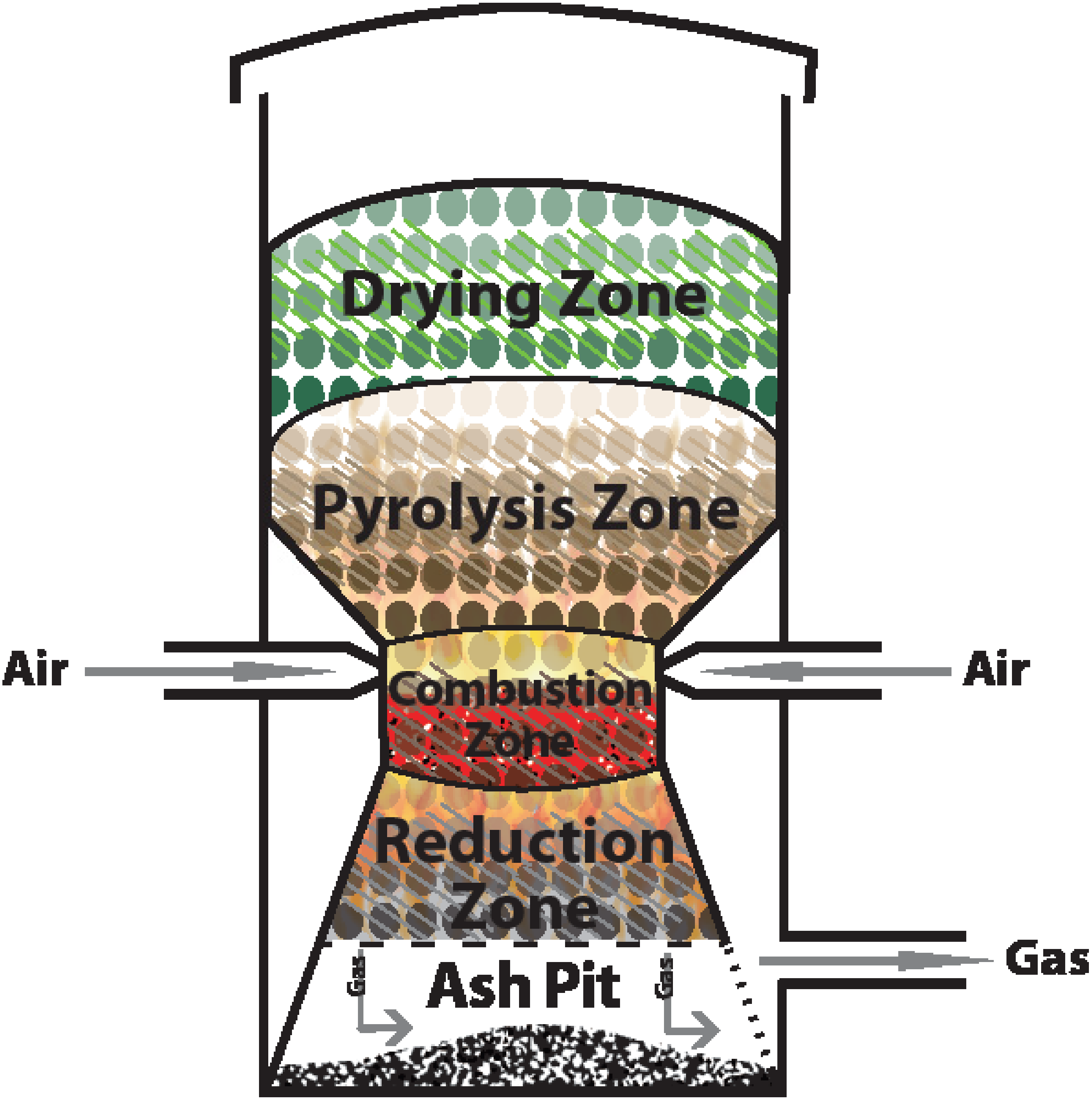


Updraft Gasifier

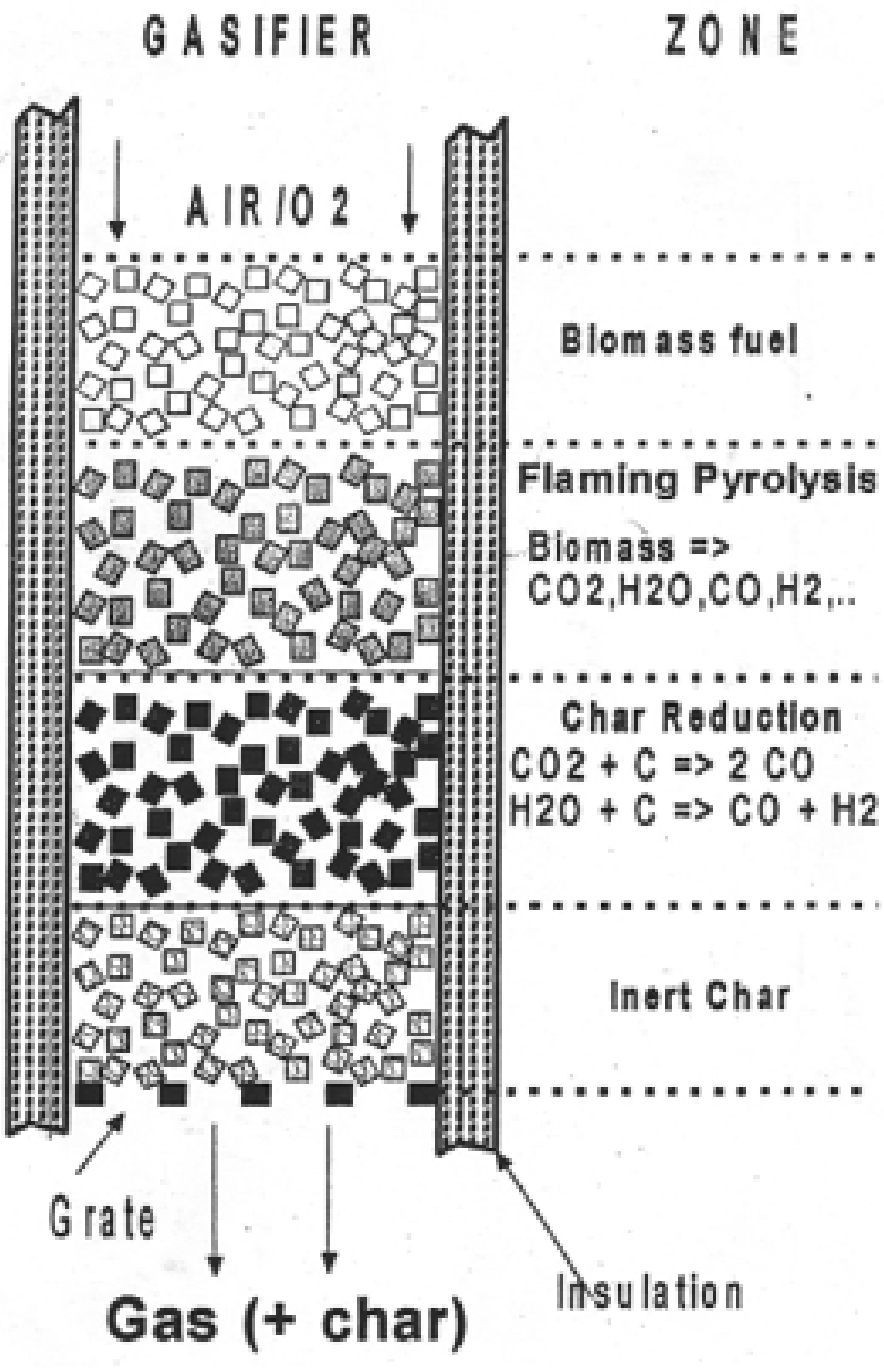


Downdraft Gasifier

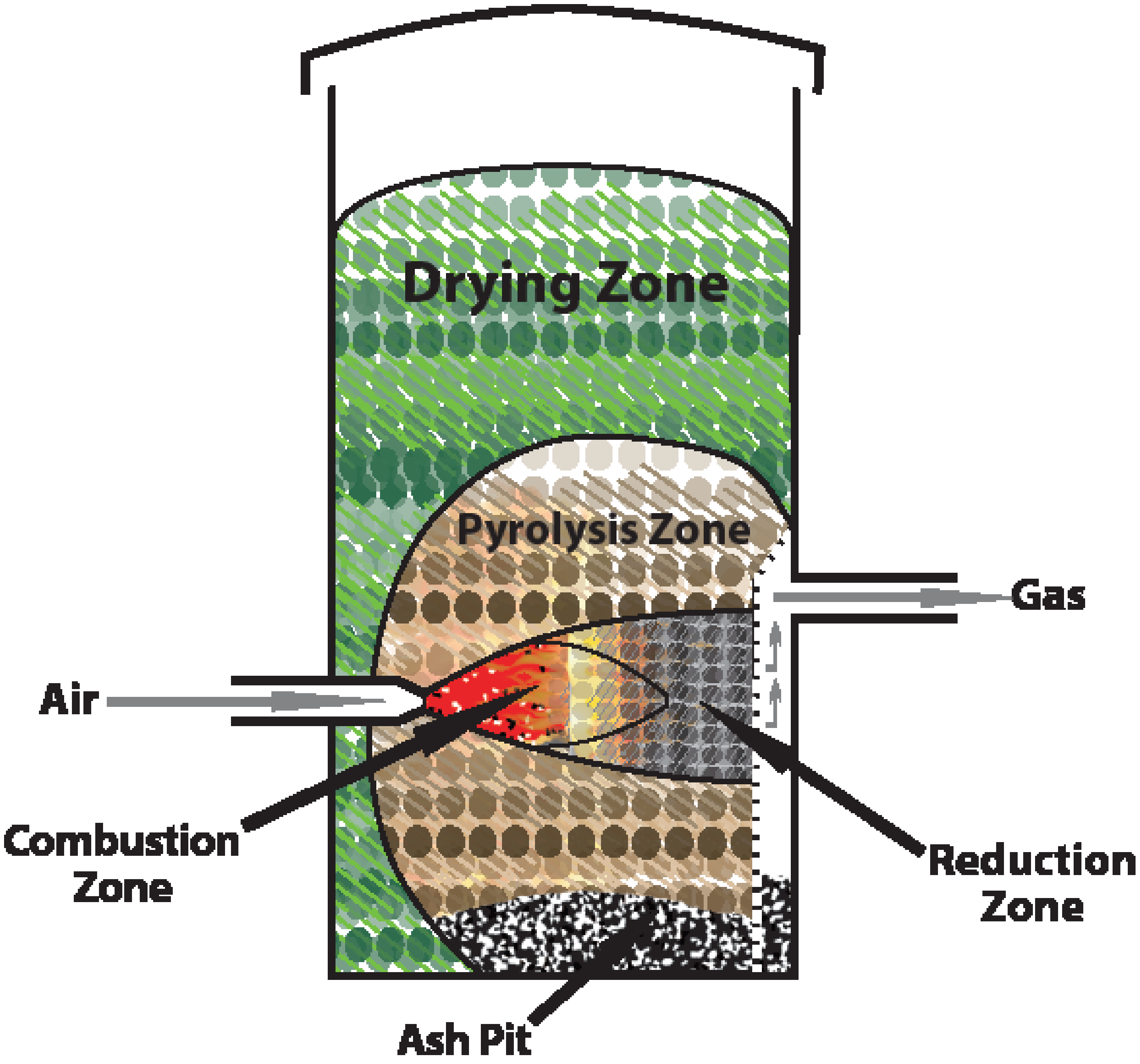
Nozzle and constriction (Imbert)



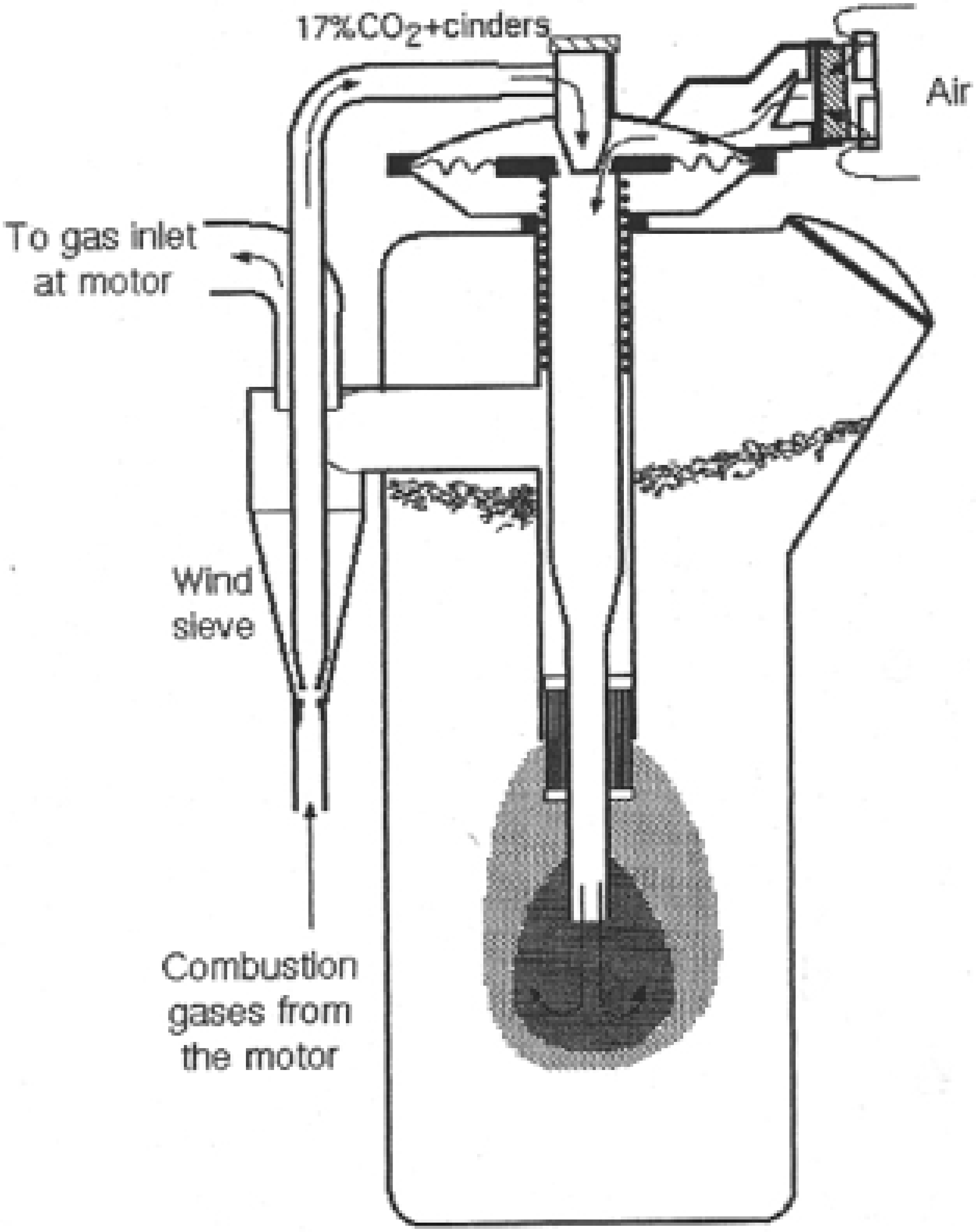
Stratified Downdraft / Open Core



Crossdraft Gasifier

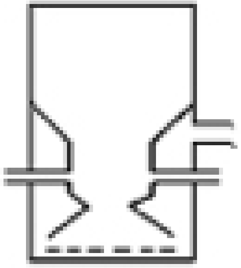


The Kalle Gasifier

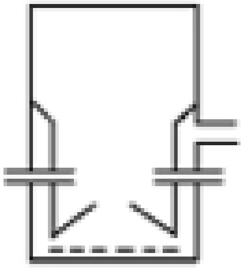


Downdraft Gasifier Types

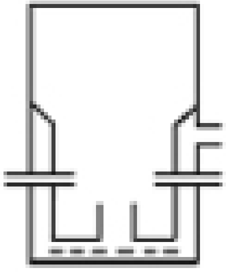
Nozzzle and Constriction Closed Top Designs (aka: Imbert type)



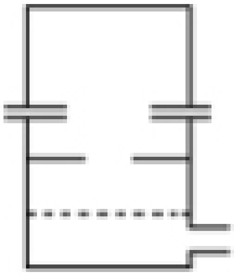
Imbert Hourglass
(double throat)



Inverted V Hearth
(Sweedish origin)



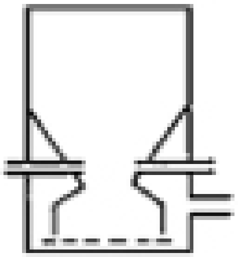
Straight Reduction Tube



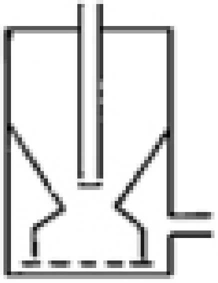
Constriction Plate

Air Inlet Variations

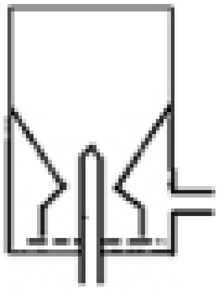
(shown with Imbert Hourglass single throat type)



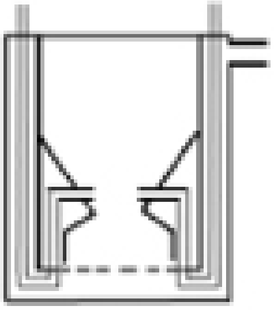
Side Inlets



Central Inlet
(down from top)

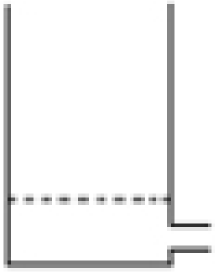


Central Inlet
(up from bottom)

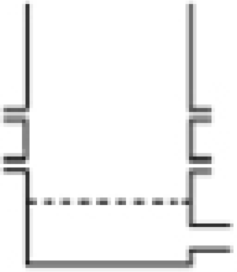


J tube
(air preheating)

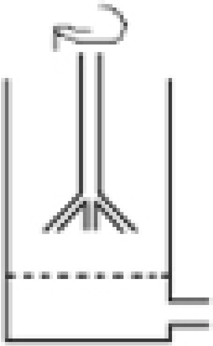
Open Core Designs



Statified Downdraft
(Tom Reed, FEMA)



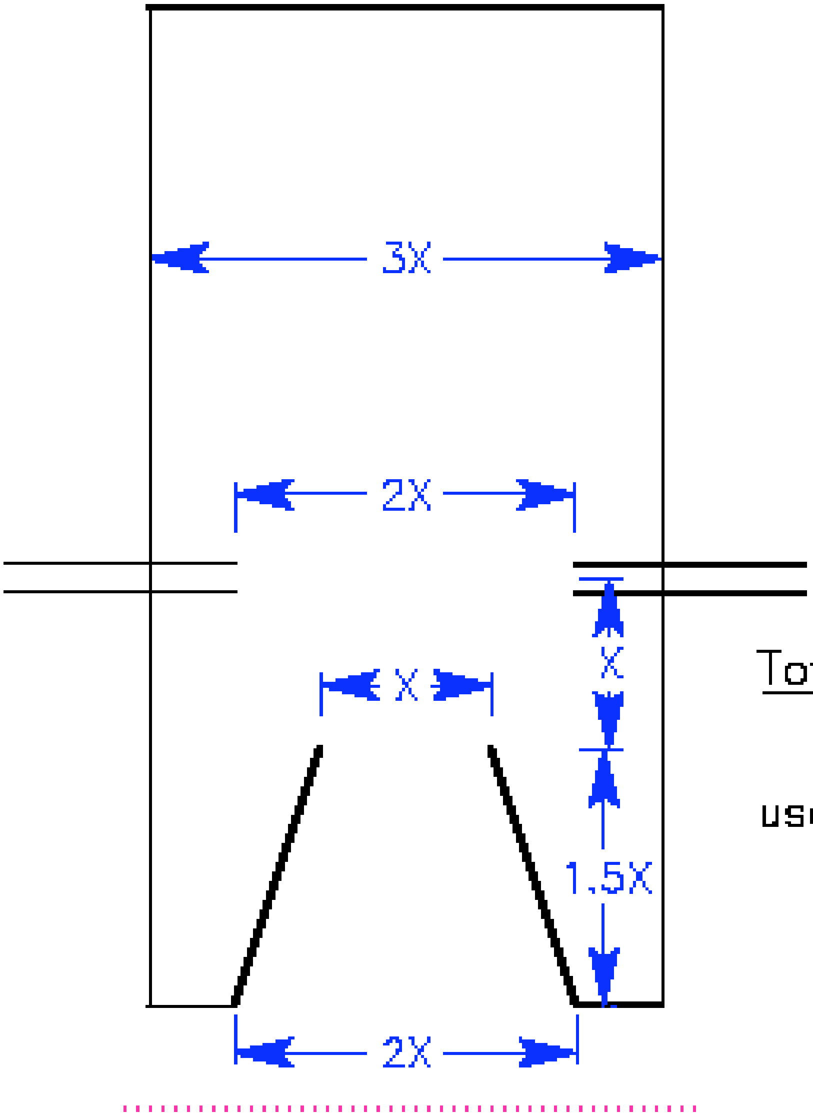
Multi-point Air Injection
(Mukunda, CPC)



Buck Rogers

General Proportions for Inverted V Hearth Downdraft Gasifier

(see charts for more detailed dimensions and variations)



$$\frac{\text{Total area of nozzles}}{(X)} = .05$$

use odd number of nozzles

ALL Power Labs June 16, 2008

Table 5-2. Imbert Nozzle and Hearth Diameters

d_r/d_h	d_h mm	d_r mm	$d_{r'}$ mm	h mm	H mm	R mm	A No.	d_m mm	$\frac{A_m \times 100}{A_h}$	$\frac{d_r}{d_h}$	$\frac{h}{d_h}$	Range of Gas Output max. Nm^3/h	Range of Gas Output min. Nm^3/h	Maximum Wood Consumption kg/h	Air Blast Velocity Vm m/s
268/60	60	268	150	80	256	100	5	7.5	7.8	4.5	1.33	30	4	14	22.4
268/80	80	268	176	95	256	100	5	9.0	6.4	3.3	1.19	44	5	21	23.0
268/100	100	268	202	100	256	100	5	10.5	5.5	2.7	1.00	63	8	30	24.2
268/120	120	268	216	110	256	100	5	12.0	5.0	2.2	0.92	90	12	42	26.0
300/100	100	300	208	100	275	115	5	10.5	5.5	3.0	1.00	77	10	36	29.4
300/115	115	300	228	105	275	115	5	11.5	5.0	2.6	0.92	95	12	45	30.3
300/130	130	300	248	110	275	115	5	12.5	4.6	2.3	0.85	115	15	55	31.5
300/150	150	300	258	120	275	115	5	14.0	4.4	2.0	0.80	140	18	67	30.0
400/130	130	400	258	110	370	155	7	10.5	4.6	3.1	0.85	120	17	57	32.6
400/150	135	400	258	120	370	155	7	12.0	4.5	2.7	0.80	150	21	71	32.6
400/175	175	400	308	130	370	155	7	13.5	4.2	2.3	0.74	190	26	90	31.4
400/200	200	400	318	145	370	153	7	16.0	3.9	2.0	0.73	230	33	110	31.2

Variables not given in figure are defined as follows:

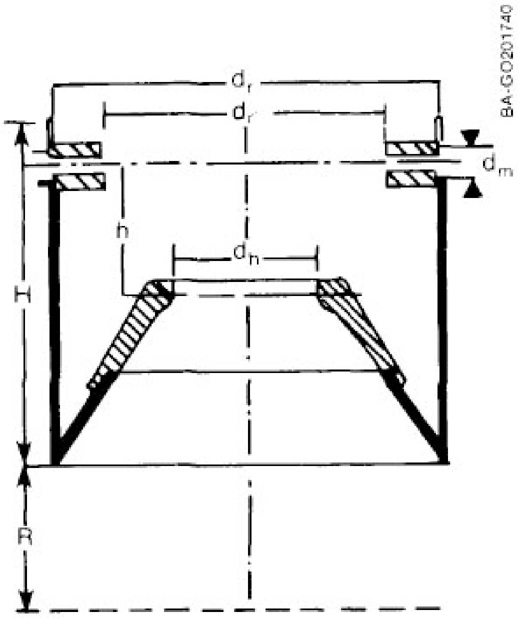
d_m = inner diameter of the tuyere.

A_m = sum of cross sectional areas of the air jet openings in the tuyeres.

A_h = cross sectional area of the throat.

A = number of tuyeres.

Source: Kaupp 1984a, Table 5; Fig. 75.



Typical Vehicle Gasifier/Engine System

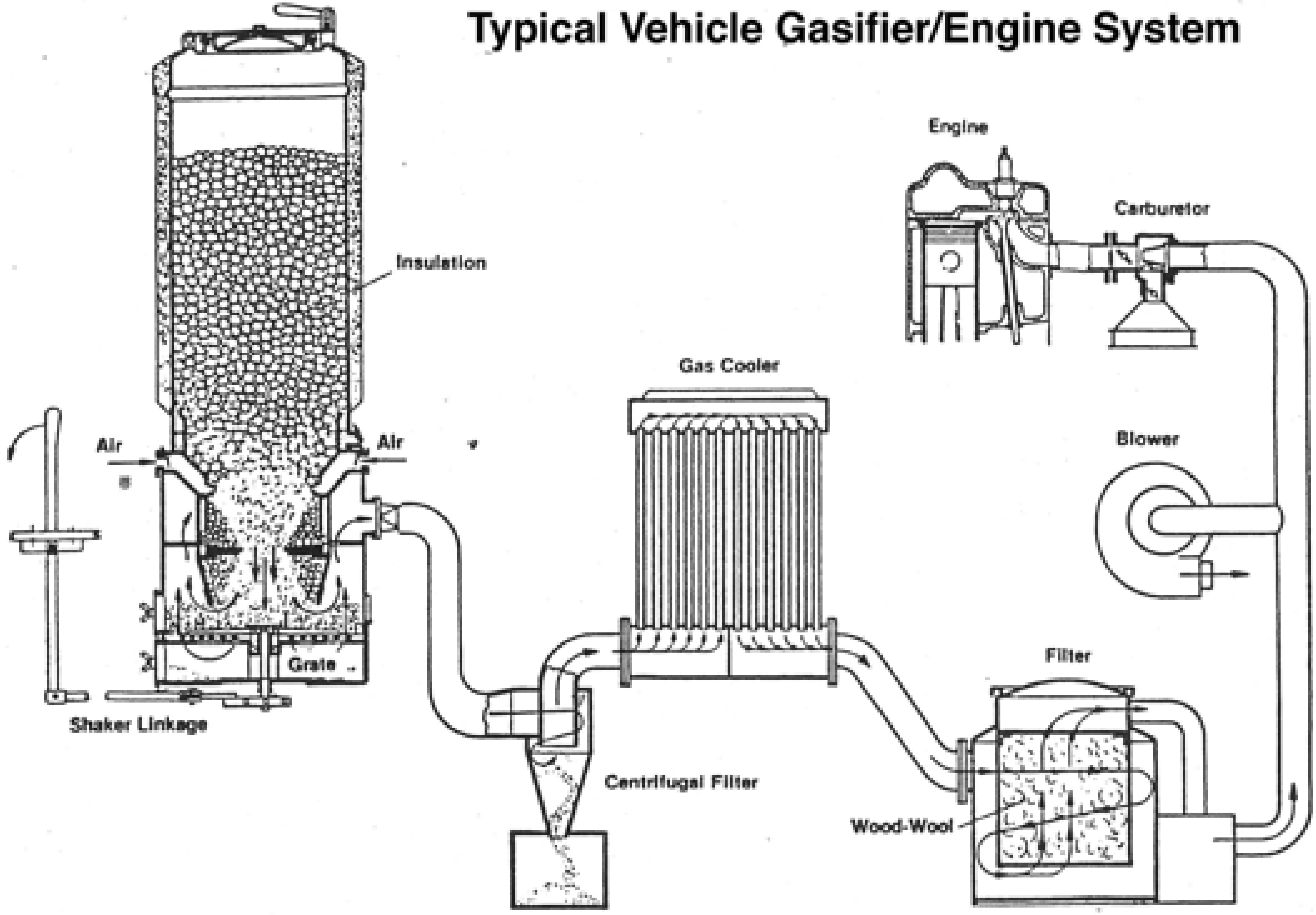
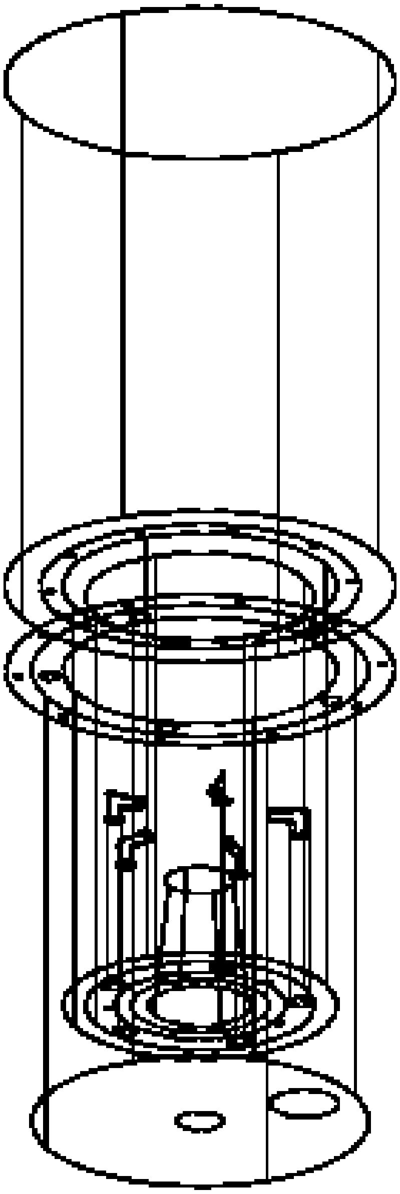
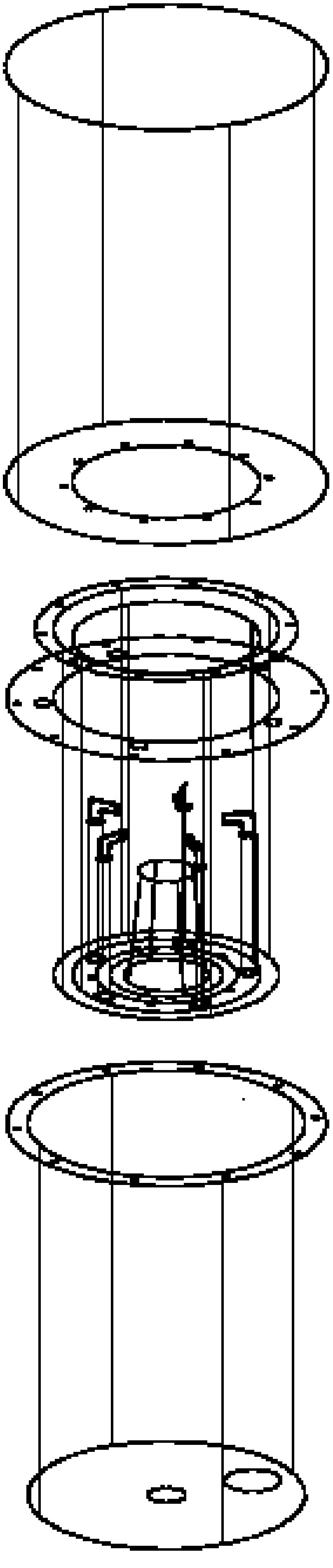


Fig. 8-3. Typical vehicle gasifier system showing cyclone and gas cooler (Source: Adapted from Skov 1974)

GEK v2.0 Main Assembly

Gas Cowling, Reactor, Hopper

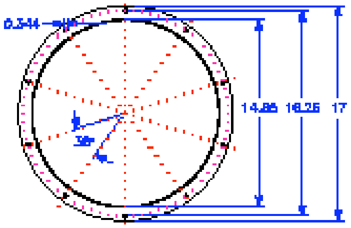




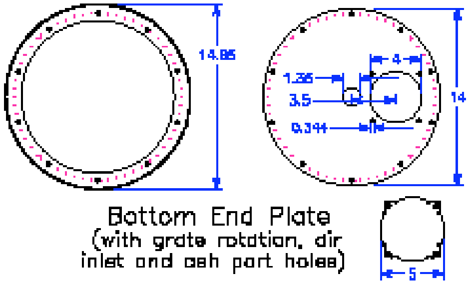
GEK Flange Rings and End Plates v3.0

(Cut from 1/8" mild steel sheet)

Gas Cowling

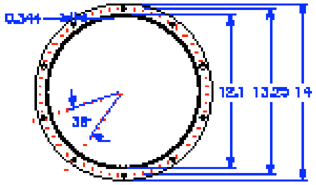


Top Rim Flange

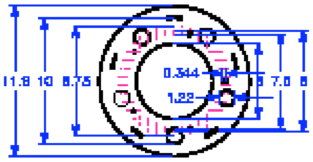


Bottom End Plate
(with grate rotation, air
inlet and ash port holes)

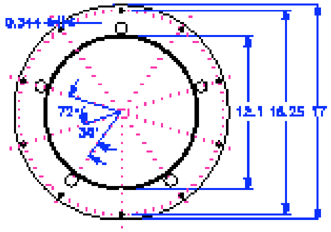
Downdraft Reactor



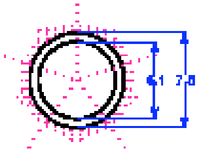
Top Rim Flange



Bottom End Plate

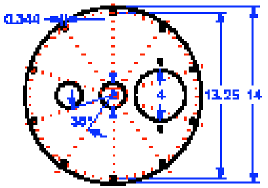


Perimeter
Mounting Flange

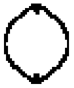


Reduction Bell
End Plate
(or cut center
to desired size)

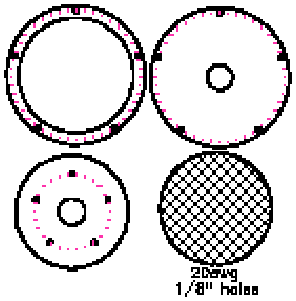
Hopper, Filter, Cyclone, Fan, Burner, Grate



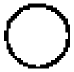
Top Cover for
Reactor or Hopper
(holes for fuel fill and
top down air config)



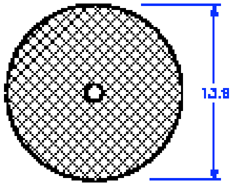
Lid



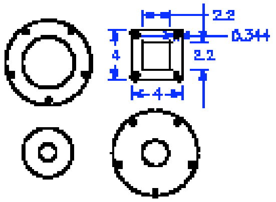
Filter, Mesh & Lid



Swirl Burner



Ash Grate
1/8" thick
3/16" holes

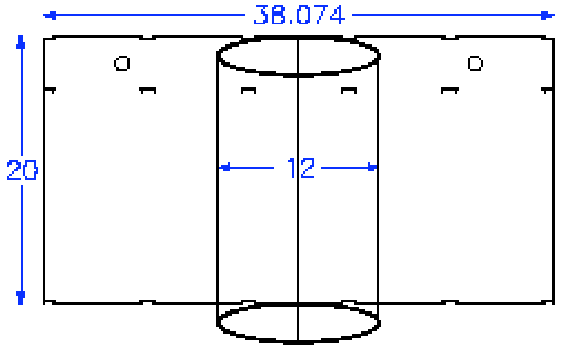


Before building, check for more recent versions at: www.gekgasifier.com
ALL Power Labs 1010 Murray Street Berkeley, CA 94710. 8/09. jim@allpowerlabs.org

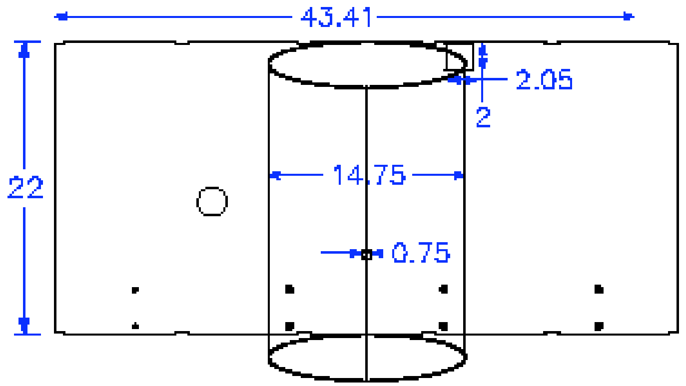
For more info, see www.allpowerlabs.com/gasification/downloads.html

GEK Vessel Tubes v3.0: rolled from flat sheet

(Cut from 1/16" thick mild steel sheet)

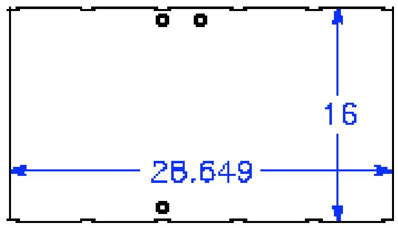


Downdraft Reactor Outside



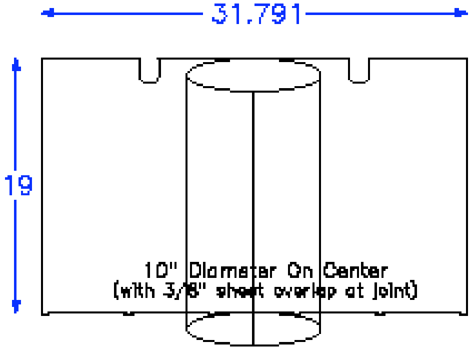
14.75" Diameter On Center
(with 3/8" sheet overlap at joint)

Gas Cowling

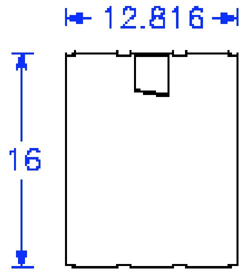


8" Diameter On Center
(with 3/8" sheet overlap at joint)

Packed Bed Filter

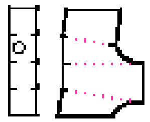


Downdraft Reactor Inside/Insulation

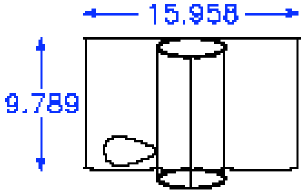


4" Dia cylinder"
(with 1/4" sheet overlap)

Cyclone

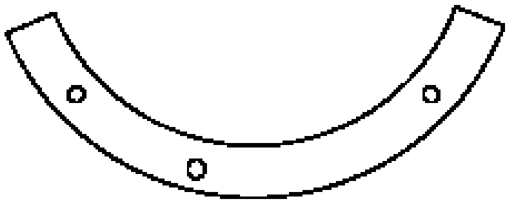


Cyclone Inlet



5" Diameter On Center
(with 1/4" sheet overlap at joint)

Swirl Burner

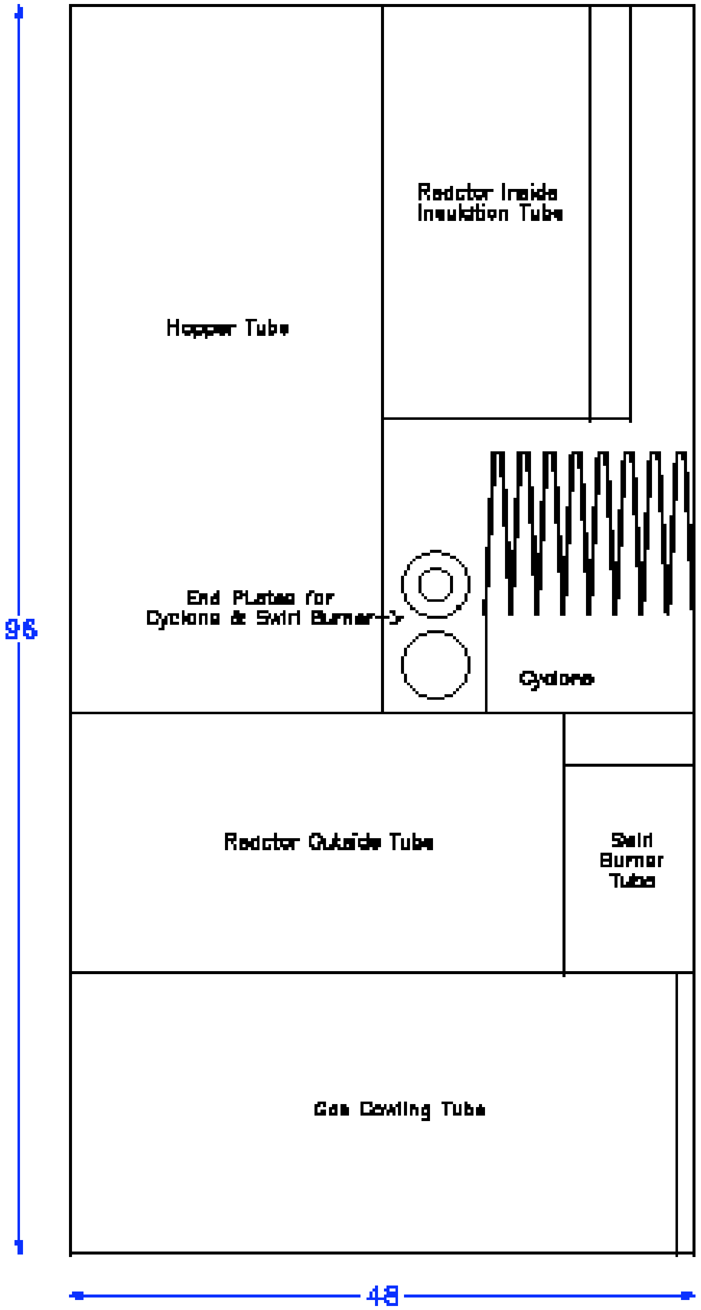


Air Neck

Before building, check for more recent versions at: www.gekgasifier.com
ALL Power Labs 1010 Murray Street Berkeley, CA 94710. 8/09. jim@allpowerlabs.org
For more info, see www.allpowerlabs.com/gasification/downloads.html

Layout for CNC Plasma Cutting

(Cut from 1/16" thick mild steel sheet)



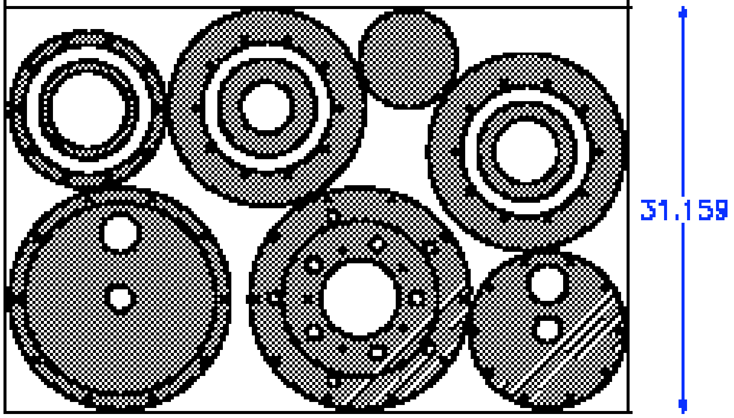
(Cut from 1/8" thick mild steel sheet)

Hatched areas are desired parts. Clear areas are drops. Three sets of flange rings and end plates can be cut from one 4' x 8' sheet.

All cuts should note male and female edges and configure machine cutting offset accordingly.

The bottom left and center circles each have two closely nested parts. When cut on the internal line, the 0.05" plasma cut width forms an offset approx equal to the thickness of the corresponding vessel tubes. One circular piece will mount around the outside of the tube. The other will mount on the inside of the tube.

The top row has one solid reduction bell end plate for user sizing, and three additional ones with precut 3", 4" and 5" ID centers.

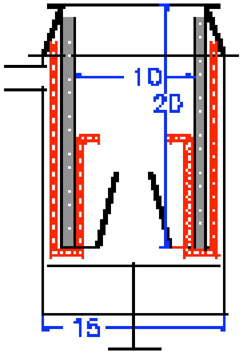


(v0.8. Before building, check www.allpowerlabs.org/gasification/gek for most recent version before building.)

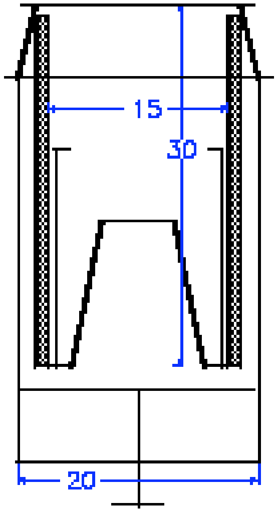
ALL Power Labs, 1010 Murray Street Berkeley, CA 94710. 4/18/08. Jimmmason@shotlarnupta.com

GEK Scale–up Sizing Steps

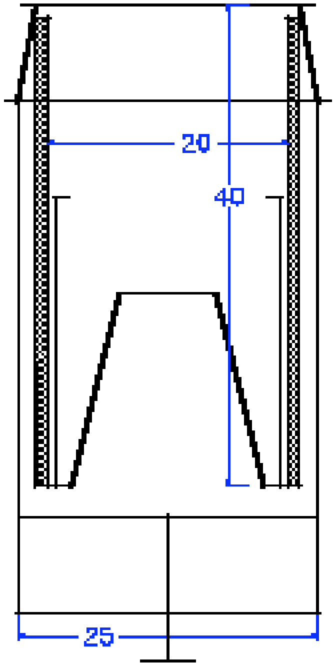
Each step based on common north american tank sizes.
Gas flow rates estimated with traditional Imbert sizing chart



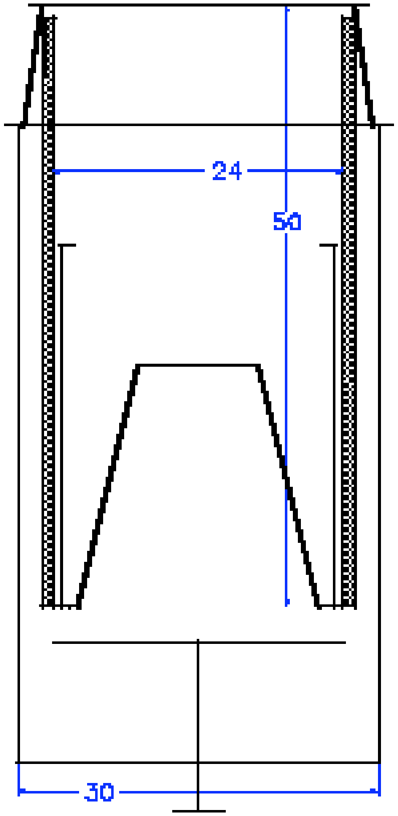
Small Block GEK
2.5–**3**– 4 inch
constriction



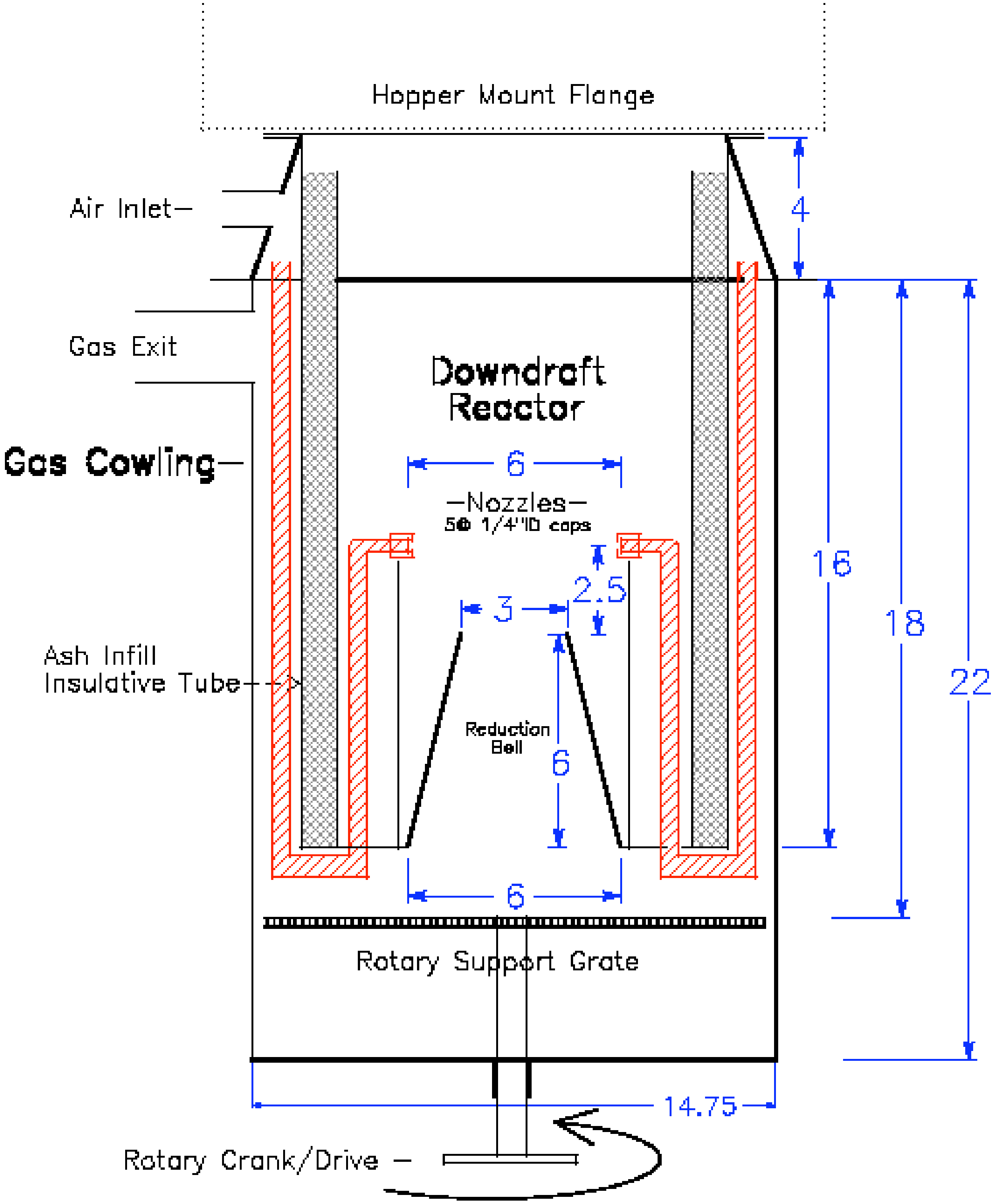
Big Block GEK
4–**6**–8 inch
constriction



Mountain GEK
6–**8**–10 inch
constriction

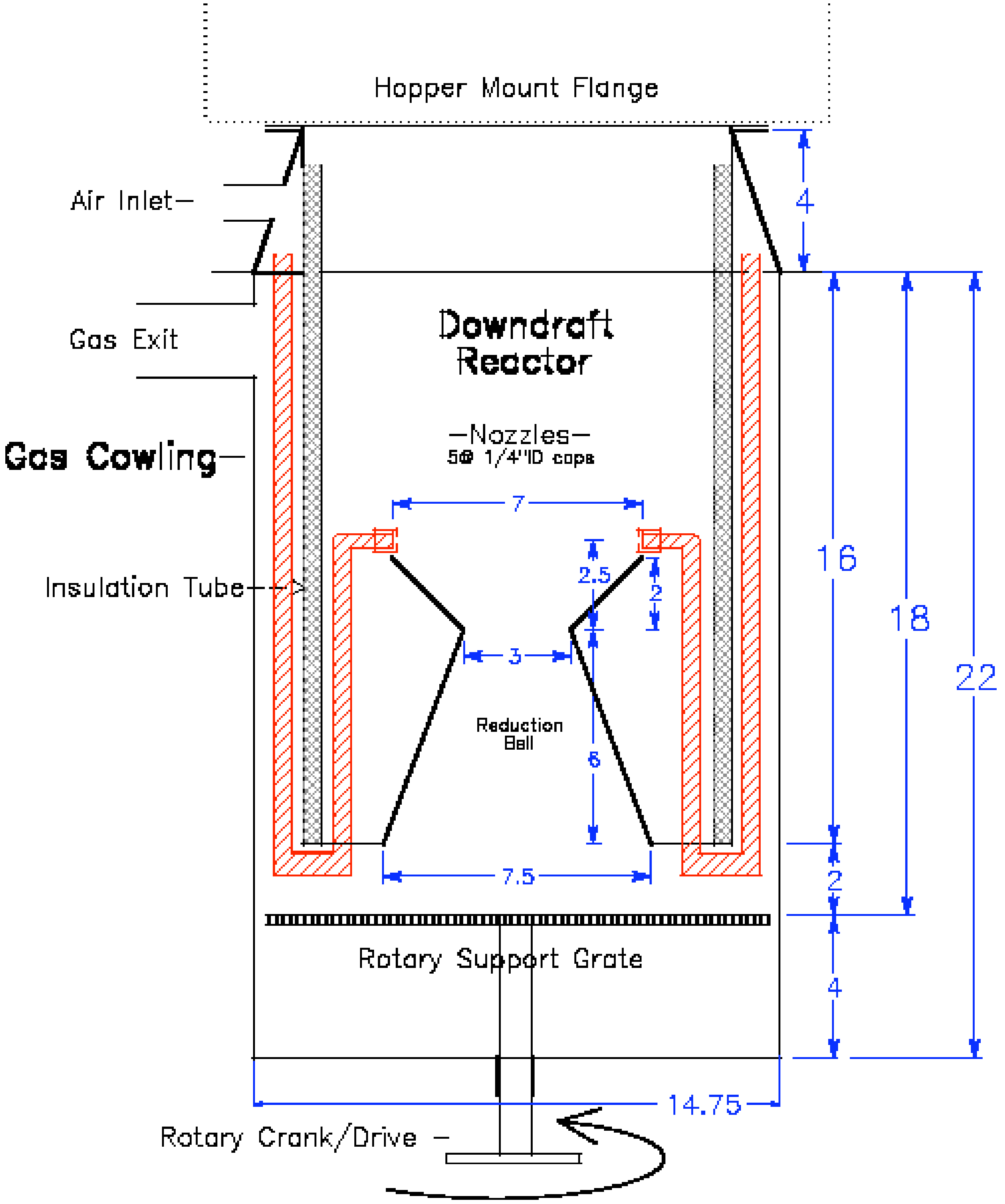


Merlin GEK
8–**10**–12 inch
constriction



GEK v3.0 Downdraft Reactor with air preheating

3" reduction restriction configuration

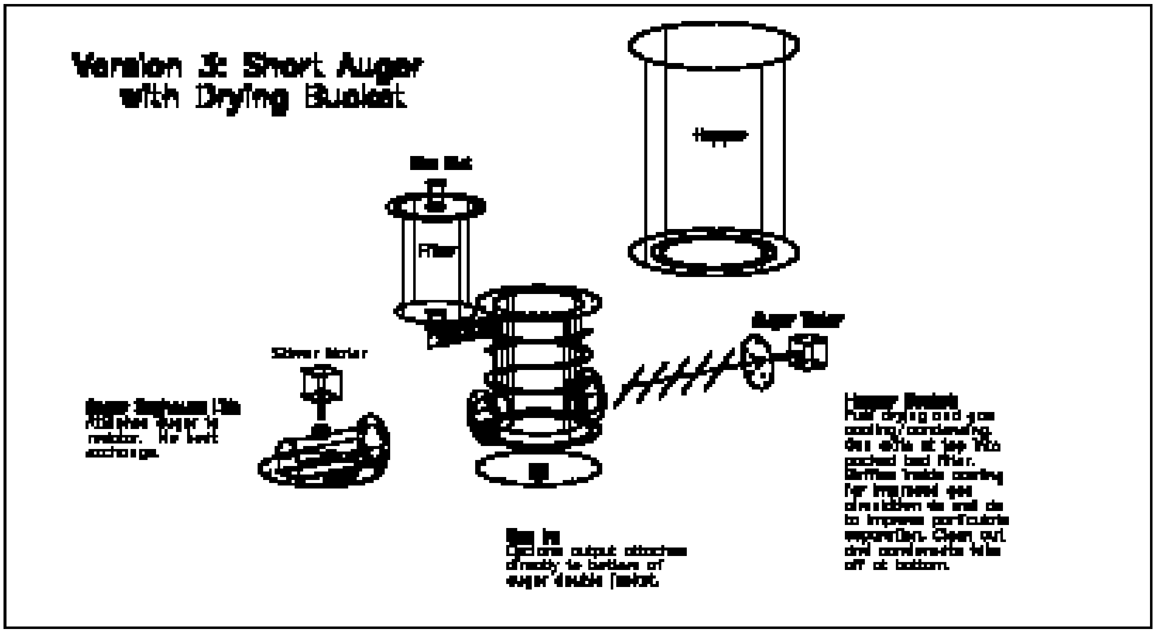


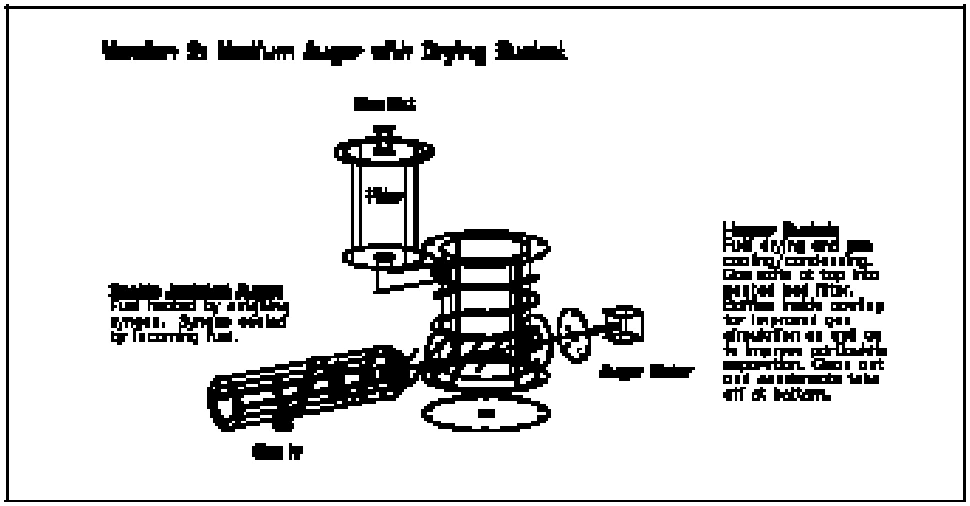
GEK 11" Reactor with J-tube air preheating

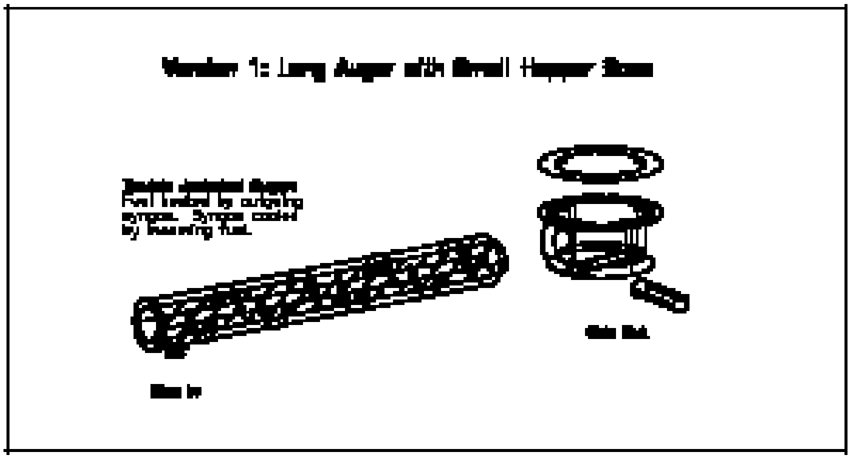
3" Imbert Hourglass Hearth

Created by Jim Mason and ALL Power Labs. 9/15/09

GEK Fuel Drying and Auger Feed Variations



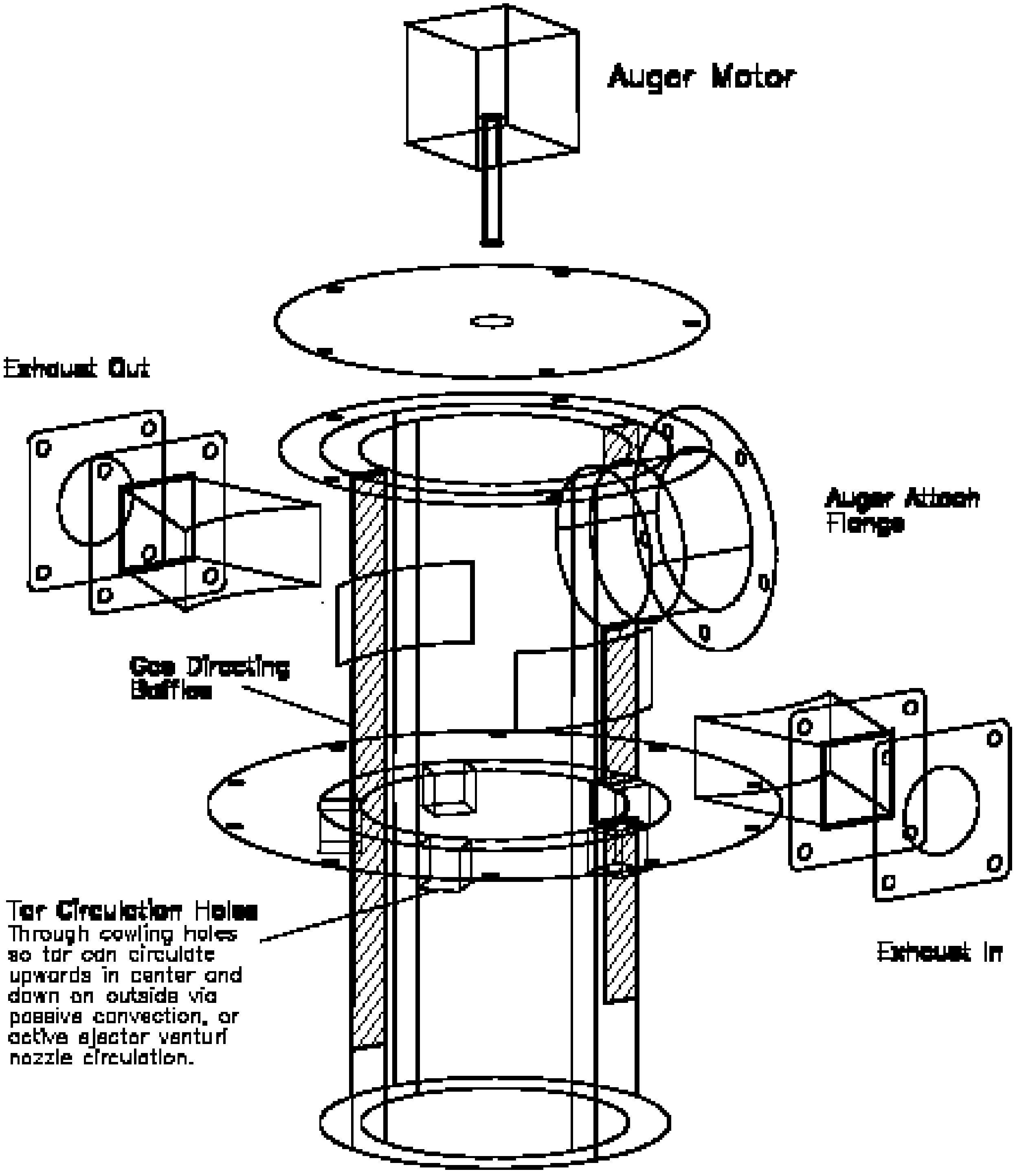




[illegible]

GEK PyroCoil Heat Exchanger

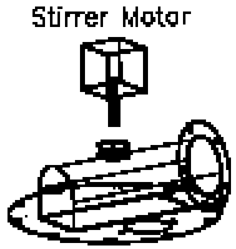
Double shell gas circulating heat exchanger inserts into reactor and drives pyrolysis zone with IC exhaust or other external heat source.



Tar Circulation Holes
Through cowling holes so tar can circulate upwards in center and down on outside via passive convection, or active ejector venturi nozzle circulation.

GEK Auger fuel feed and fuel drying/preheating system

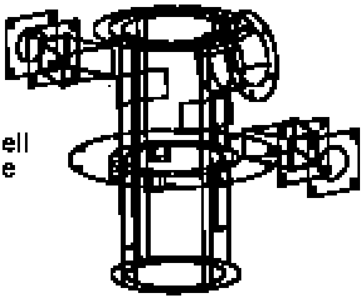
Auger Doghouse or PyroCoil reactor attachment



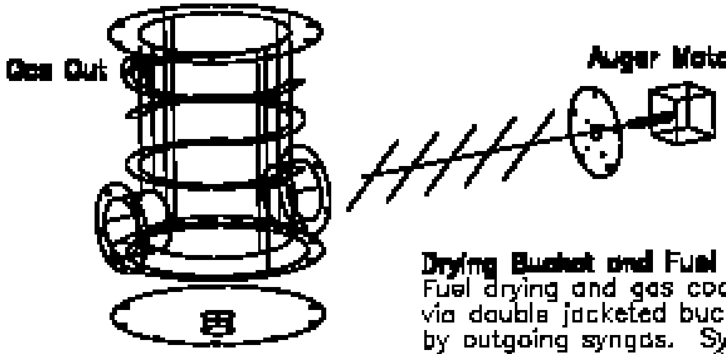
Auger Doghouse Lid:
Attaches auger to reactor. No heat exchange.

Use one or the other. Not both.

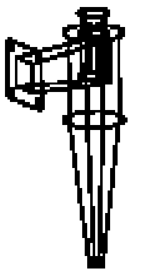
—OR—



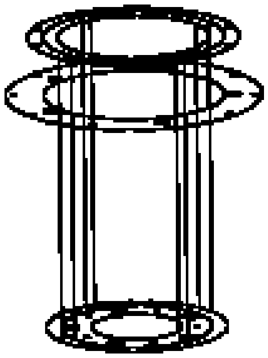
PyroCoil:
Heat exchange shell to return IC engine exhaust heat to pyrolysis zone in reactor. Replaces Auger Doghouse.



Drying Bucket and Fuel Feed Auger:
Fuel drying and gas cooling/condensing via double jacketed bucket. Fuel heated by outgoing syngas. Syngas cooling by incoming fuel. Gas exits at top into packed bed filter. Baffles inside cowling for improved gas circulation as well as to improve particulate separation. Clean out and condensate take off at bottom.



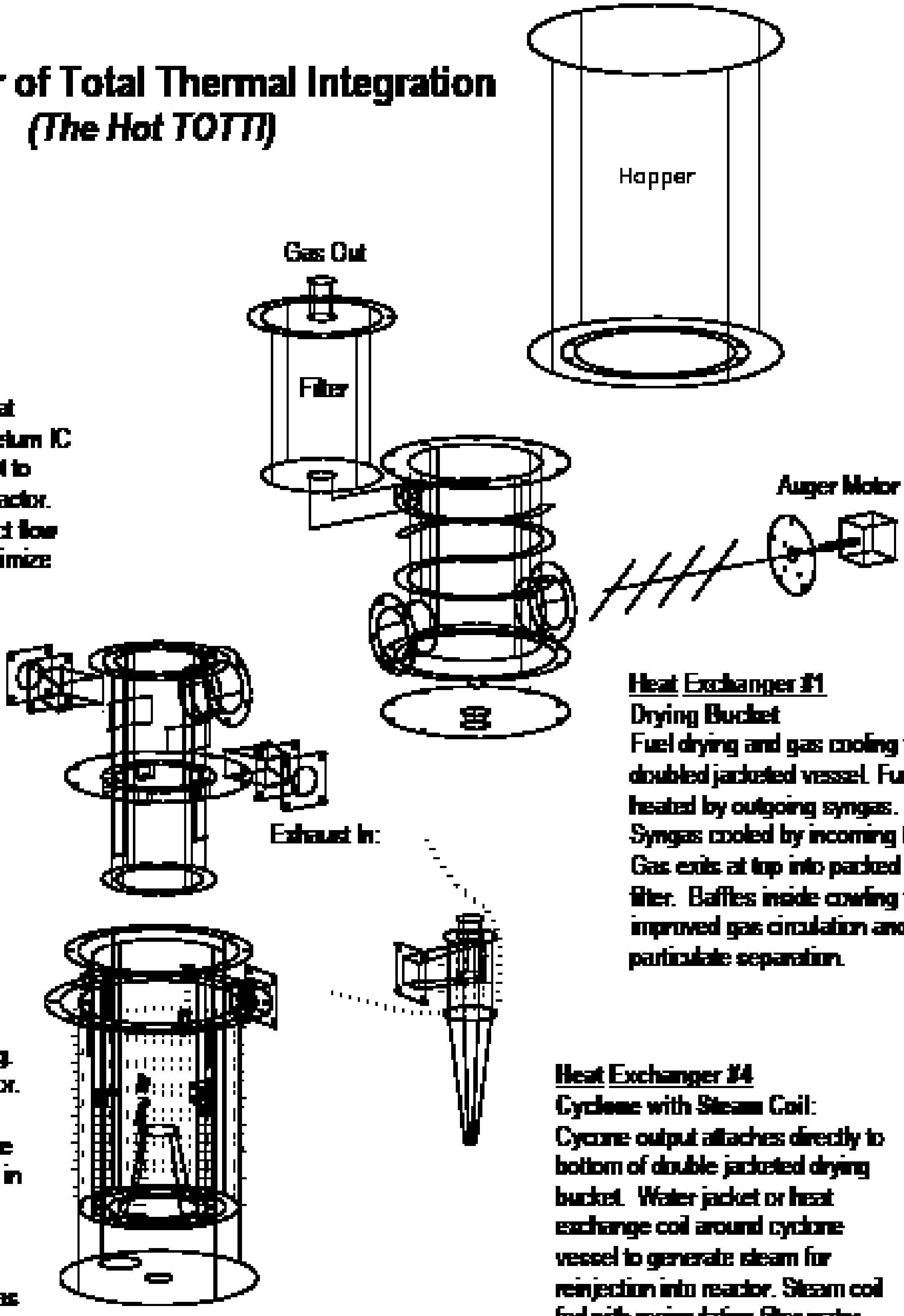
Cyclone:
Cycone output attaches directly to bottom of auger double jacket.



Downdraft Reactor:
Auger Doghouse or PyroCoil connects auger to reactor. Doghouse bolts to top of reactor. PyroCoil inserts down inside reactor.

GEK Tower of Total Thermal Integration

(The Hot TOTTI)



Heat Exchaner #2
PyroCoil
Double jacketed heat exchange shell to return IC engine exhaust heat to pyrolysis zone in reactor. Internal baffles direct flow around shell to maximize heat exchange.

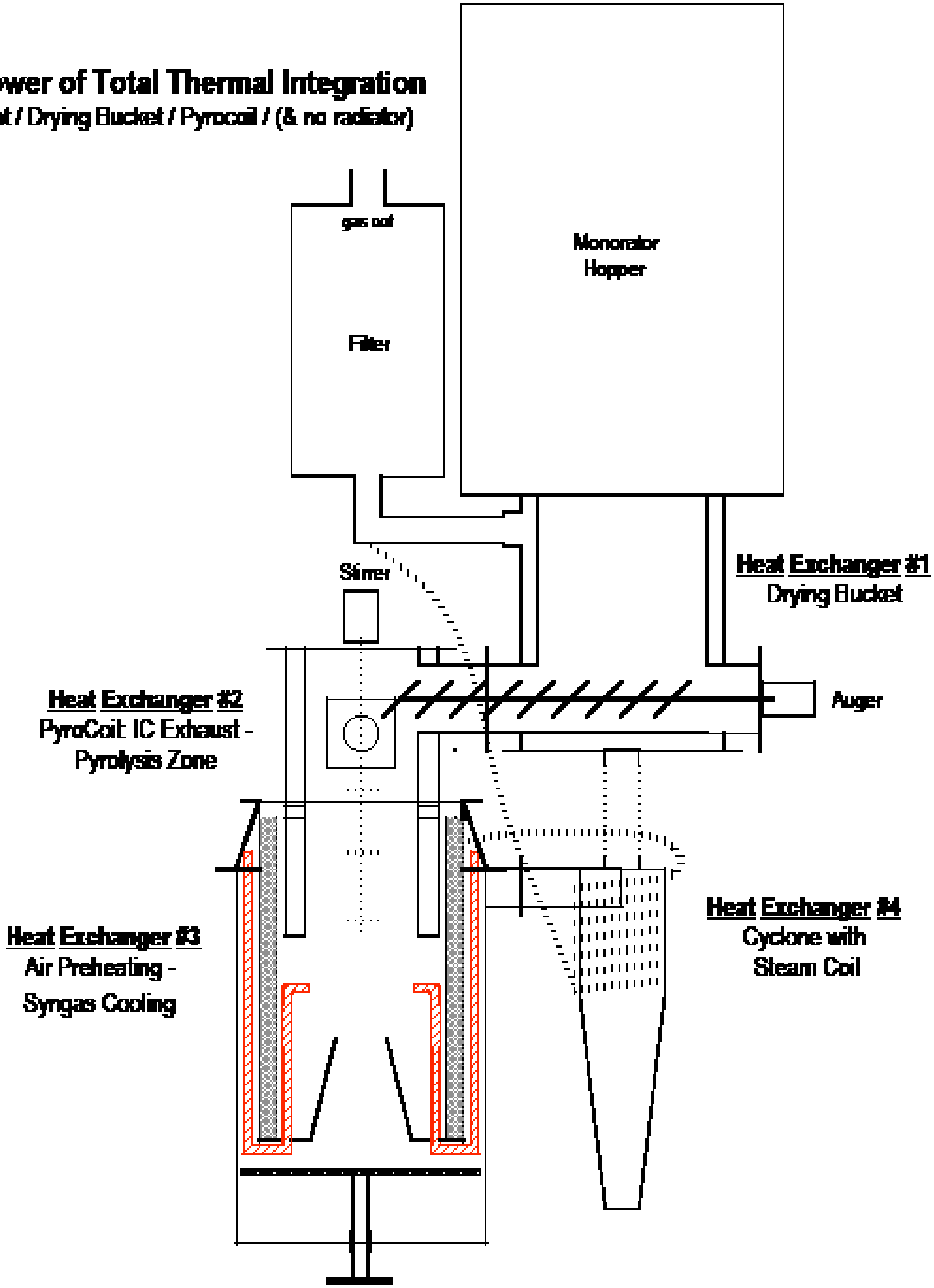
Heat Exchanger #1
Drying Bucket
Fuel drying and gas cooling via doubled jacketed vessel. Fuel heated by outgoing syngas. Syngas cooled by incoming fuel. Gas exits at top into packed bed filter. Baffles inside cowling for improved gas circulation and particulate separation.

Heat Exchanger #3
Air Preheat / Syngas cooling.
Standard GEK downdraft reactor inside Gas Cowling. PyroCoil inserts into reactor. Air intake lines made from flex corregated ss air intake lines wrap around reactor, in annular space between reactor and gas cowling. Incoming air is heated by outgoing gas. Outgoing gas is cooled by incoming air.

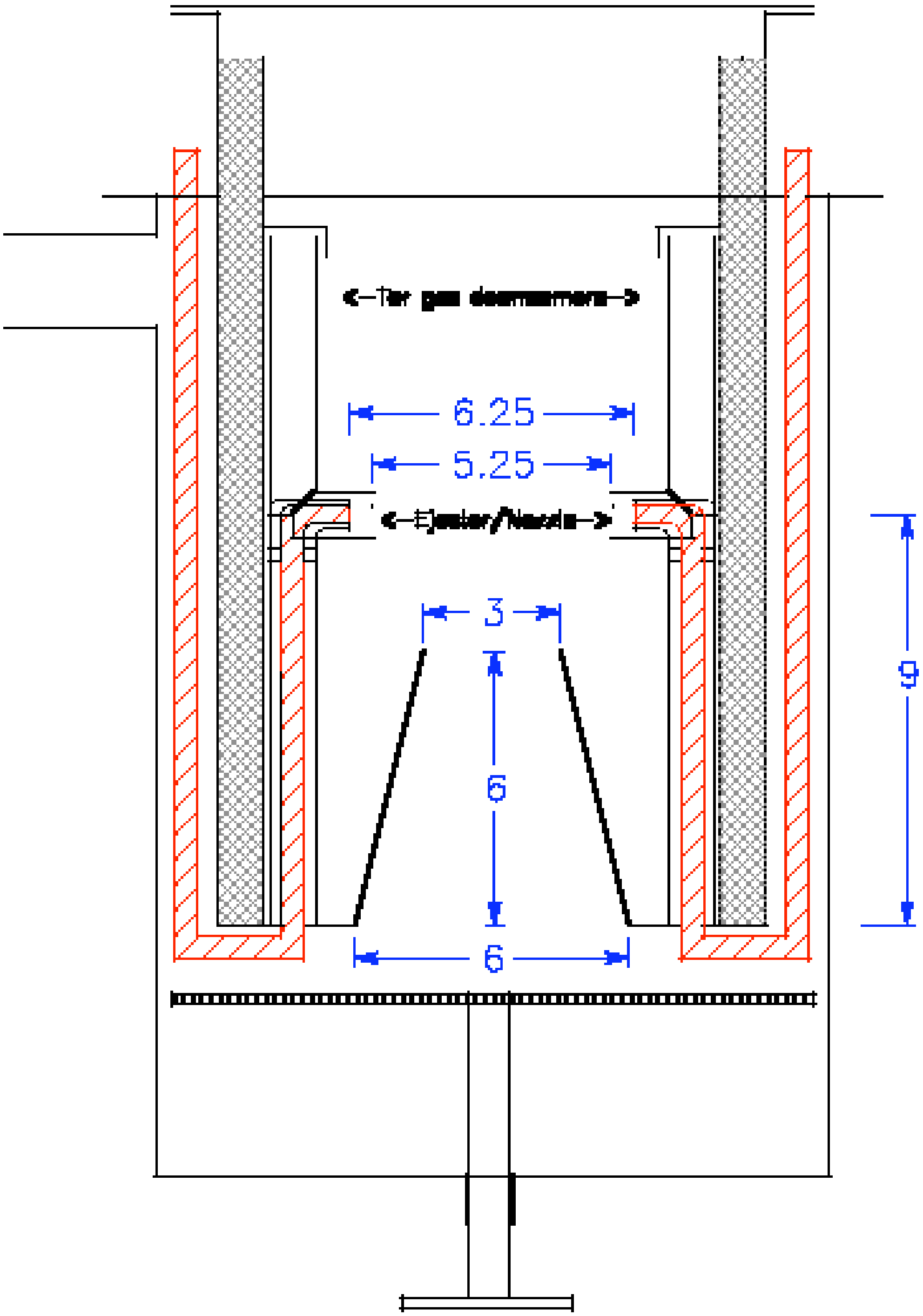
Heat Exchanger #4
Cyclone with Steam Coil:
Cycone output attaches directly to bottom of double jacketed drying bucket. Water jacket or heat exchange coil around cyclone vessel to generate steam for reinjection into reactor. Steam coil fed with recirculating filter water.

GEK Tower of Total Thermal Integration

Air Preheat / Drying Bucket / Pyrocoil / (& no radiator)



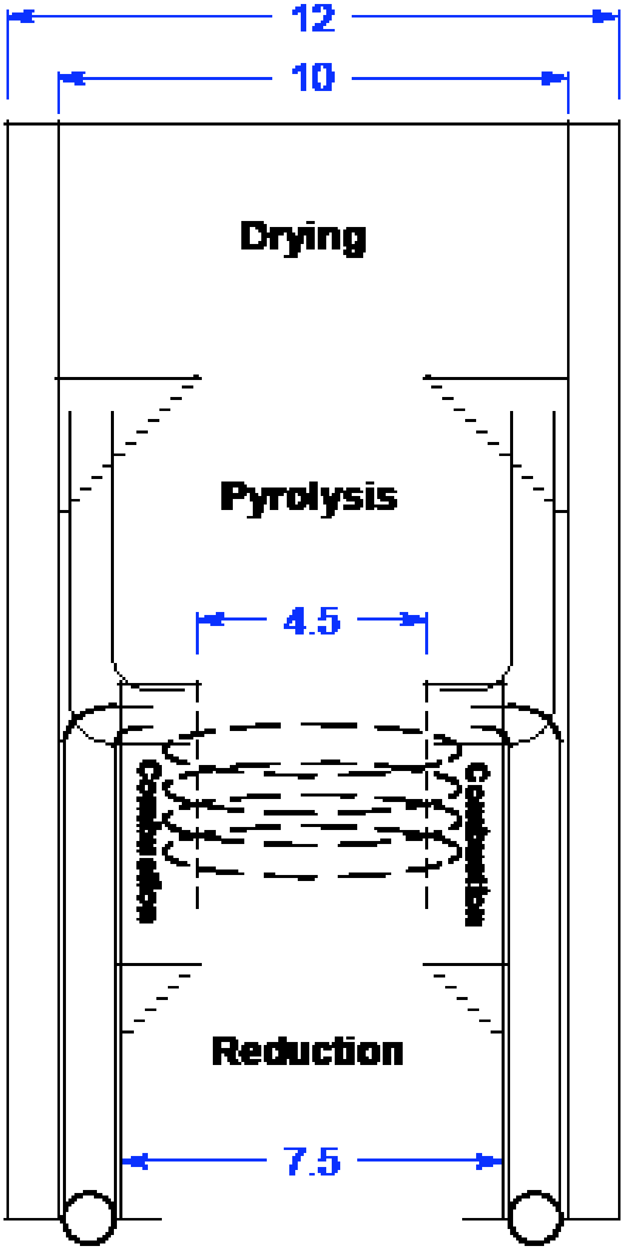
GEK Internal Tar Scavenging Ejector/Venturi Nozzles



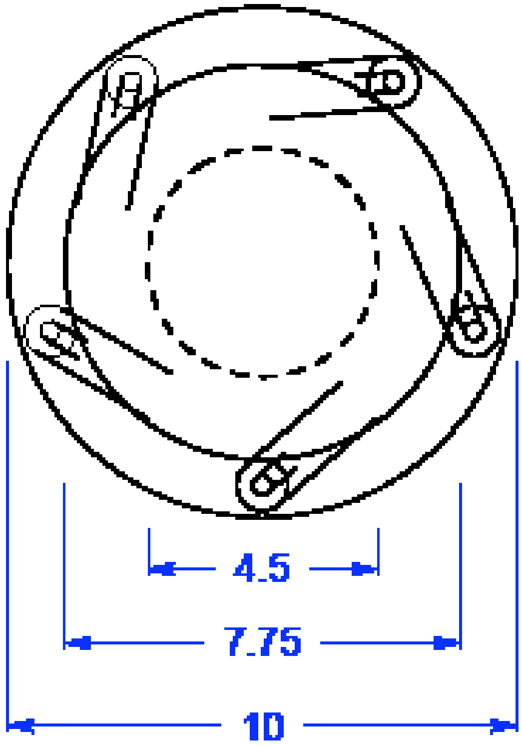
GEK Triple Hips Downdraft Study

Proposed GEK downdraft reactor insert with four zone separation, internal tar recycling, upward convection pyrolysis, and open swirl combustion chamber.

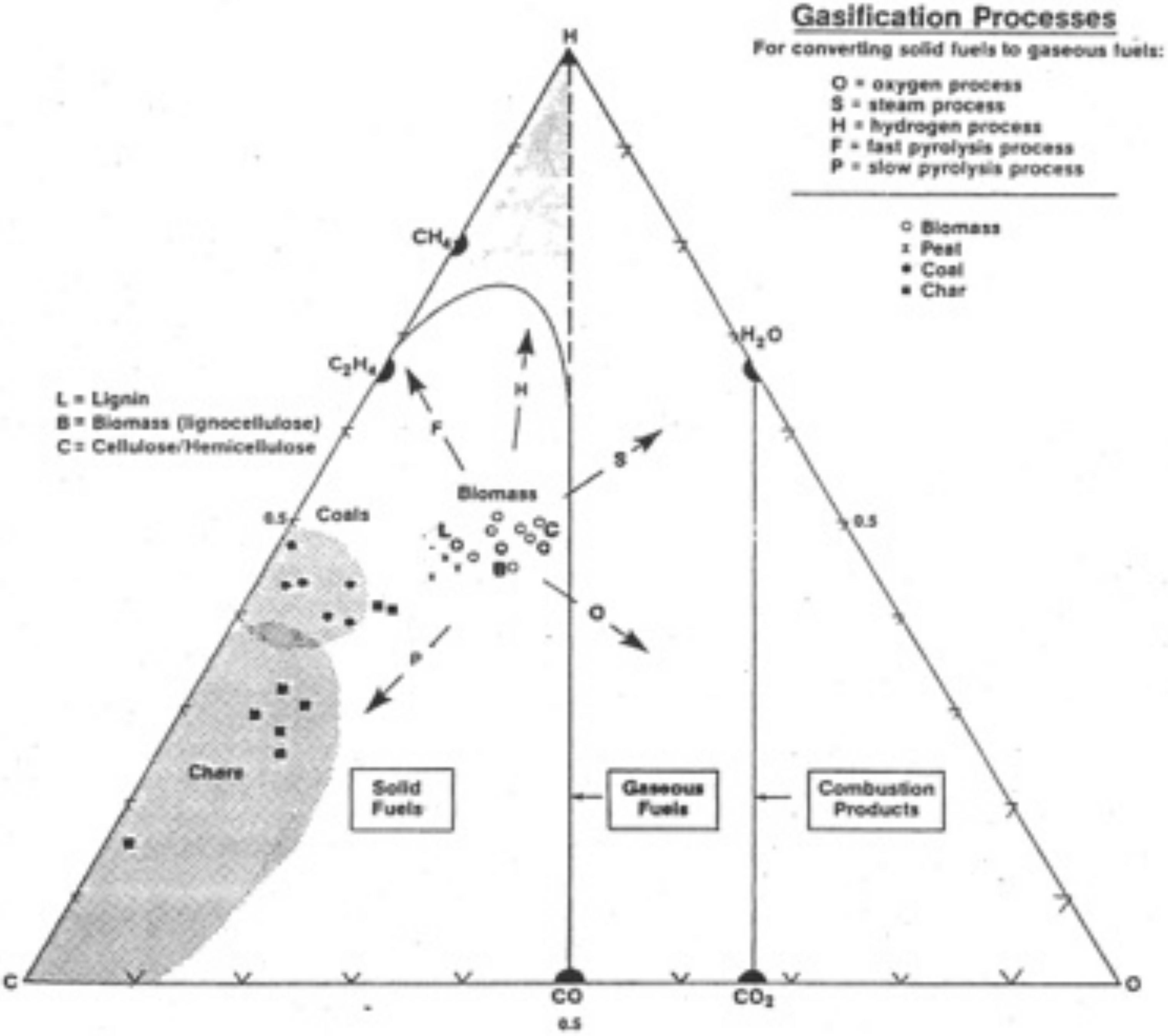
Side View of Reactor



Top View of Nozzles and Swirl Chamber

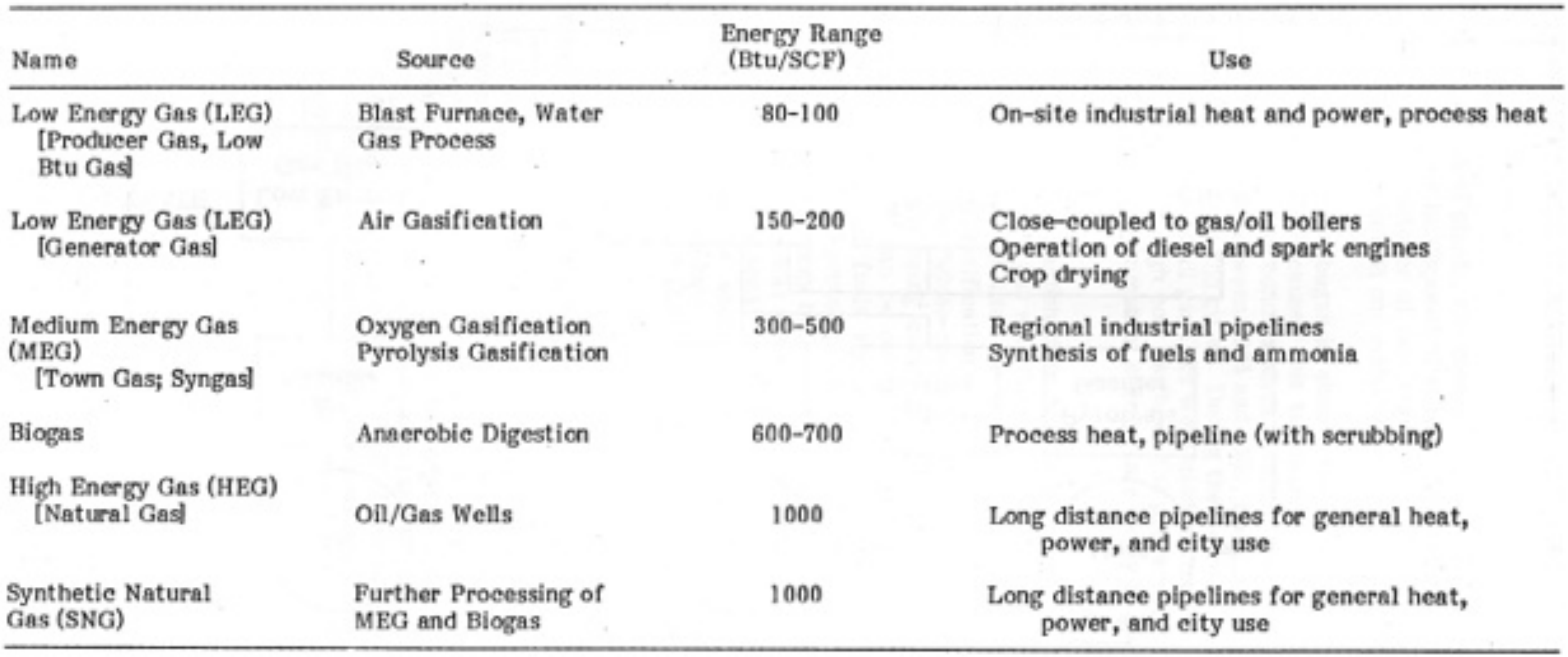


Directions of Chemical Change During Biomass Gasification



(Source: Reed, 1981)

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

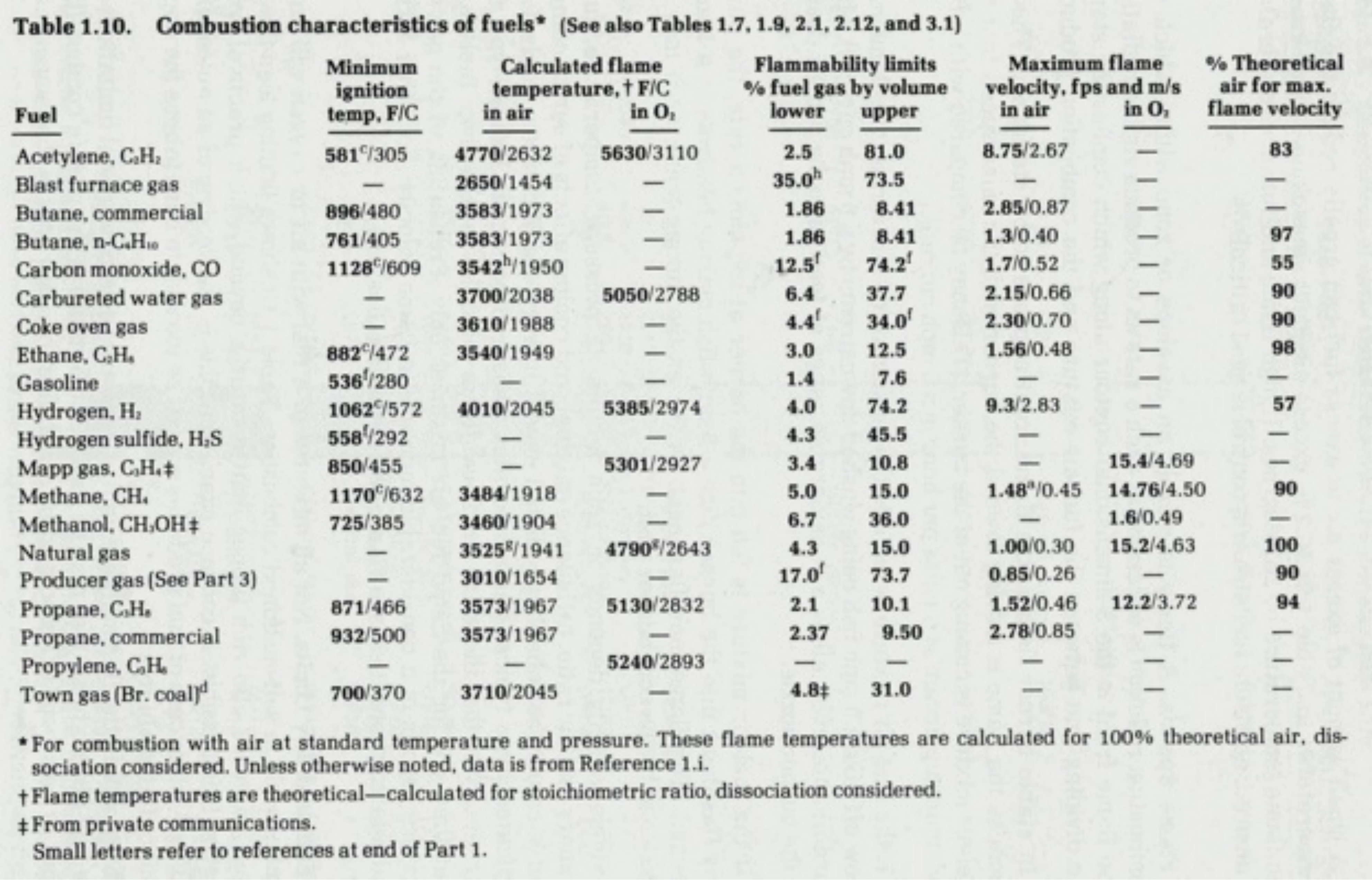


Table 1.10. Combustion characteristics of fuels* (See also Tables 1.7, 1.9, 2.1, 2.12, and 3.1)

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.

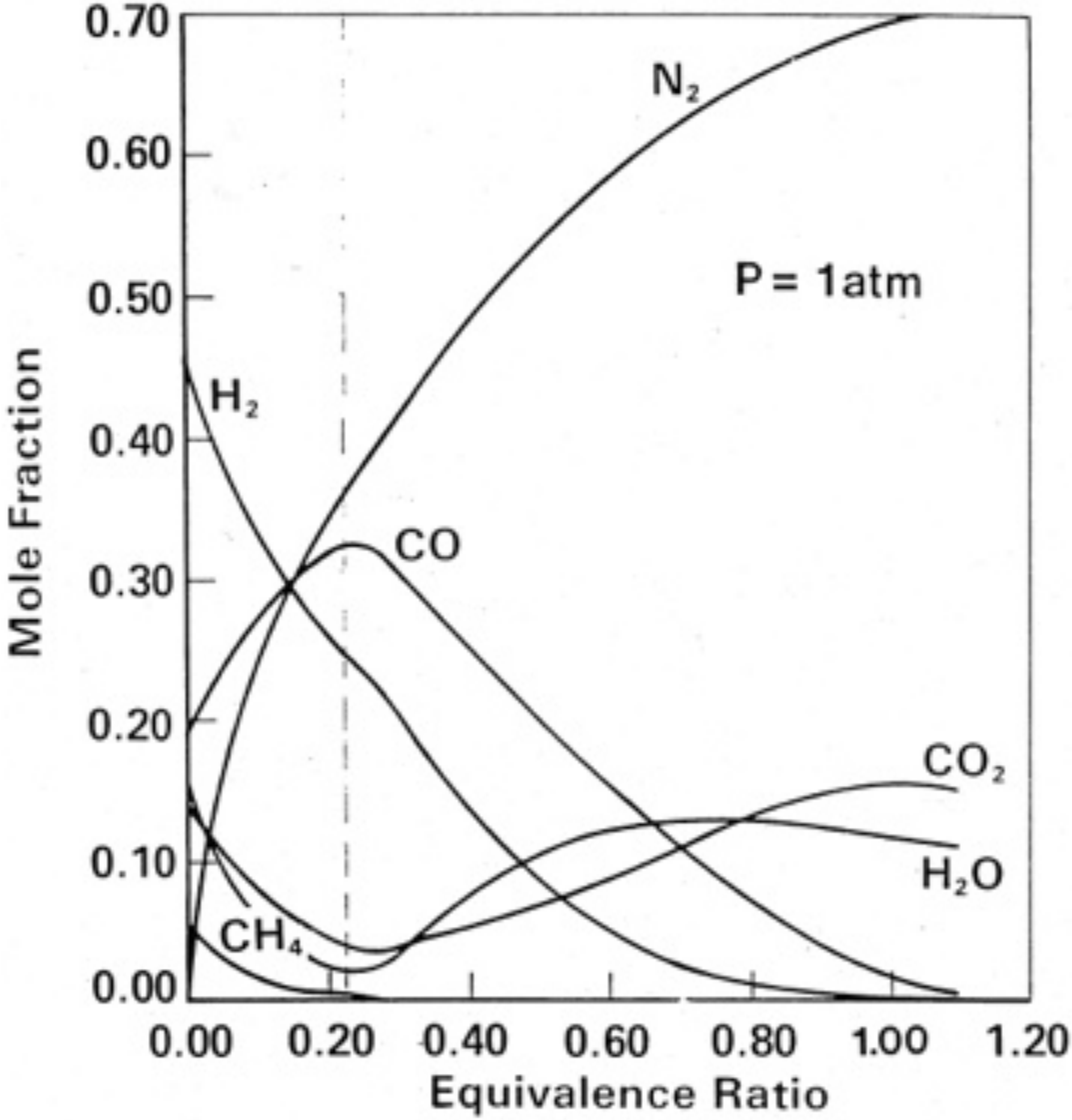


Figure S-3. Equilibrium Composition for Adiabatic Air/Biomass Reaction

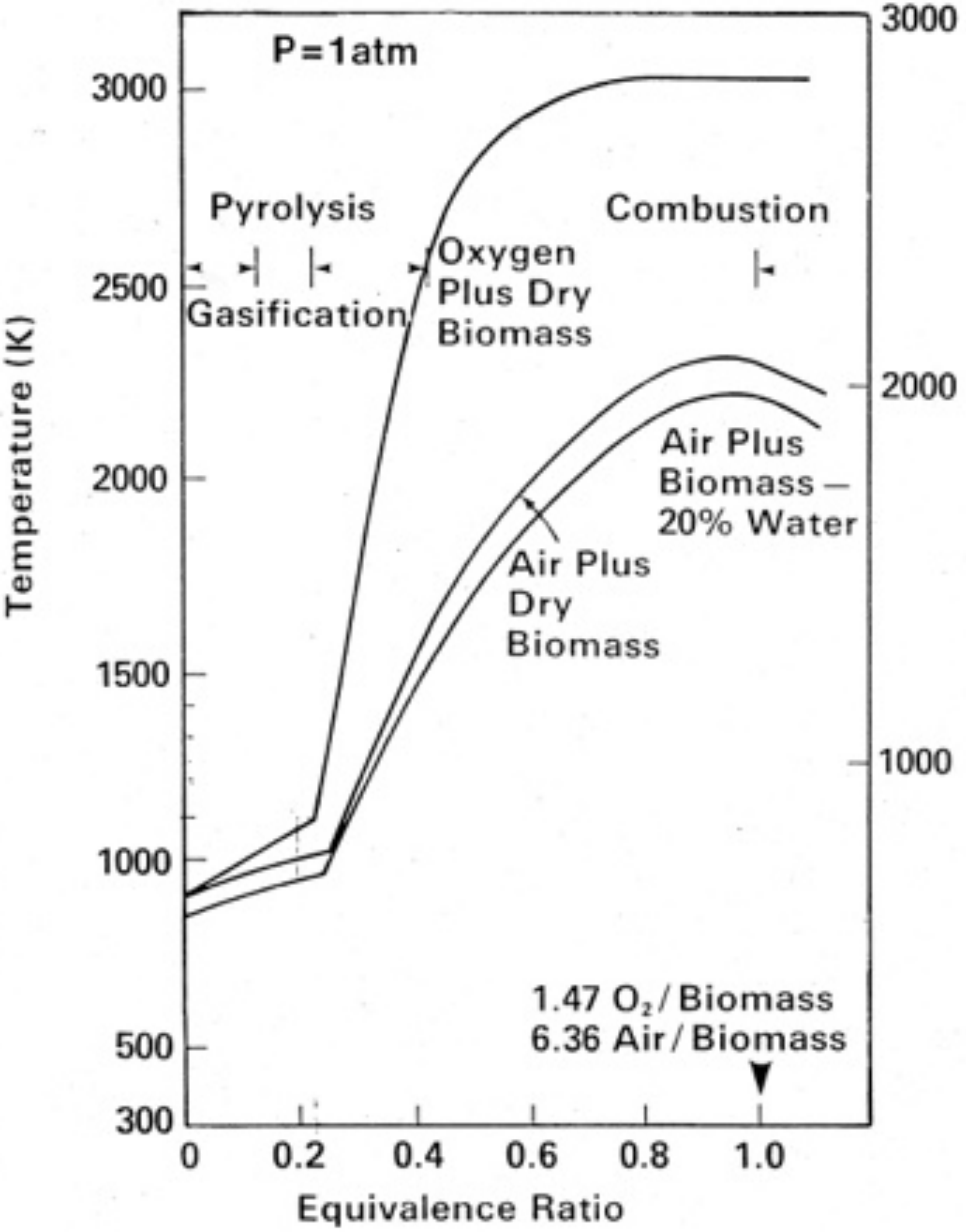


Figure S-2. Biomass Adiabatic Reaction Temperatures

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

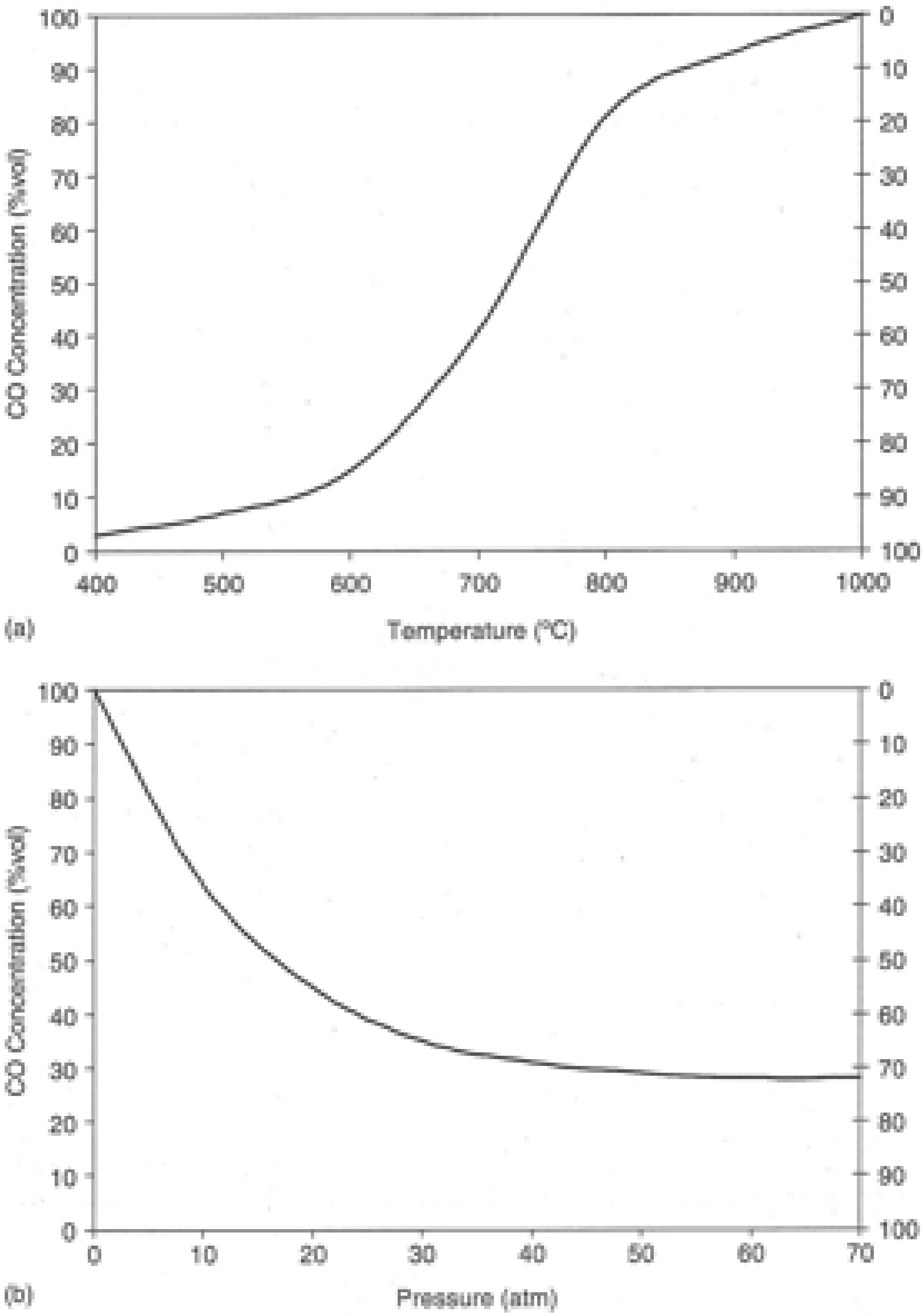


FIGURE 3.3 Boudouard reaction equilibrium: variation of carbon monoxide and carbon dioxide concentrations for gasification of carbon with oxygen (a) with temperature at a pressure of 1.0 atm, and (b) with pressure at a temperature of 800°C.

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

Reaction Equilibrium: $H_2O + C <==> H_2 + 2CO$

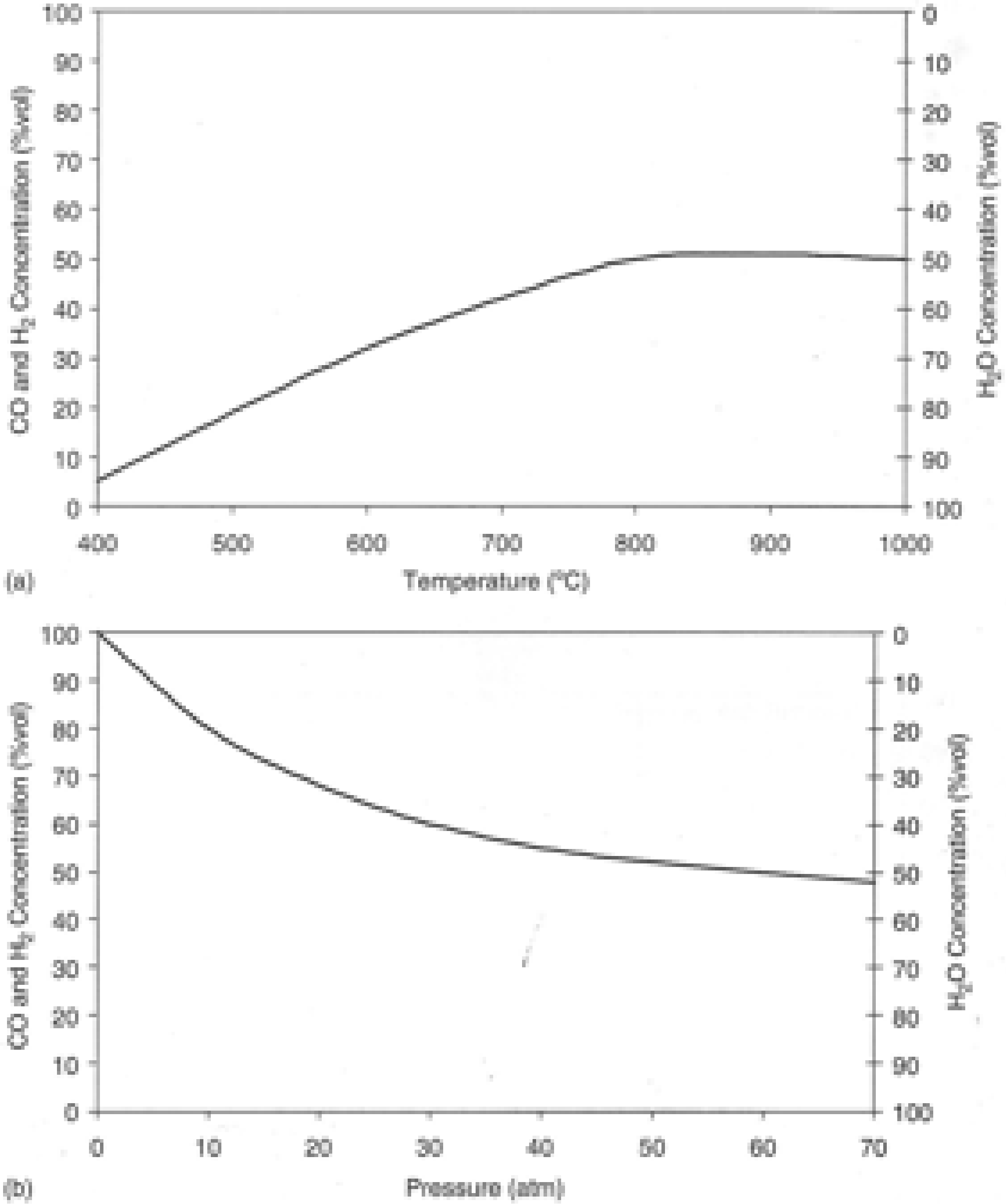


FIGURE 3.4 Water–gas reaction equilibrium: variation of carbon monoxide, hydrogen and steam (a) with temperature at a pressure of 1.0 atm, and (b) with pressure at a temperature of 800°C.

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

Reaction Equilibrium: C + H2 <==> CH4

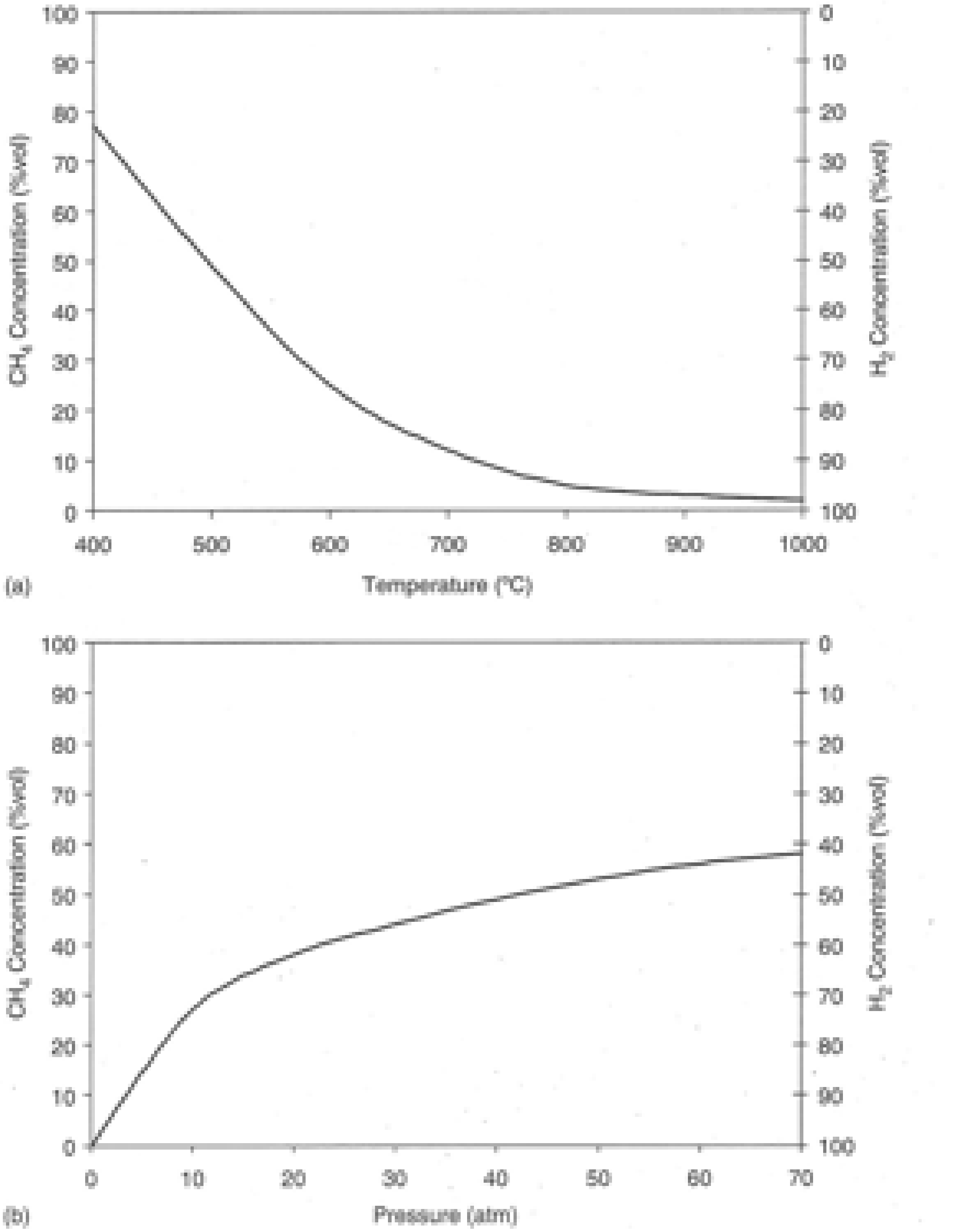
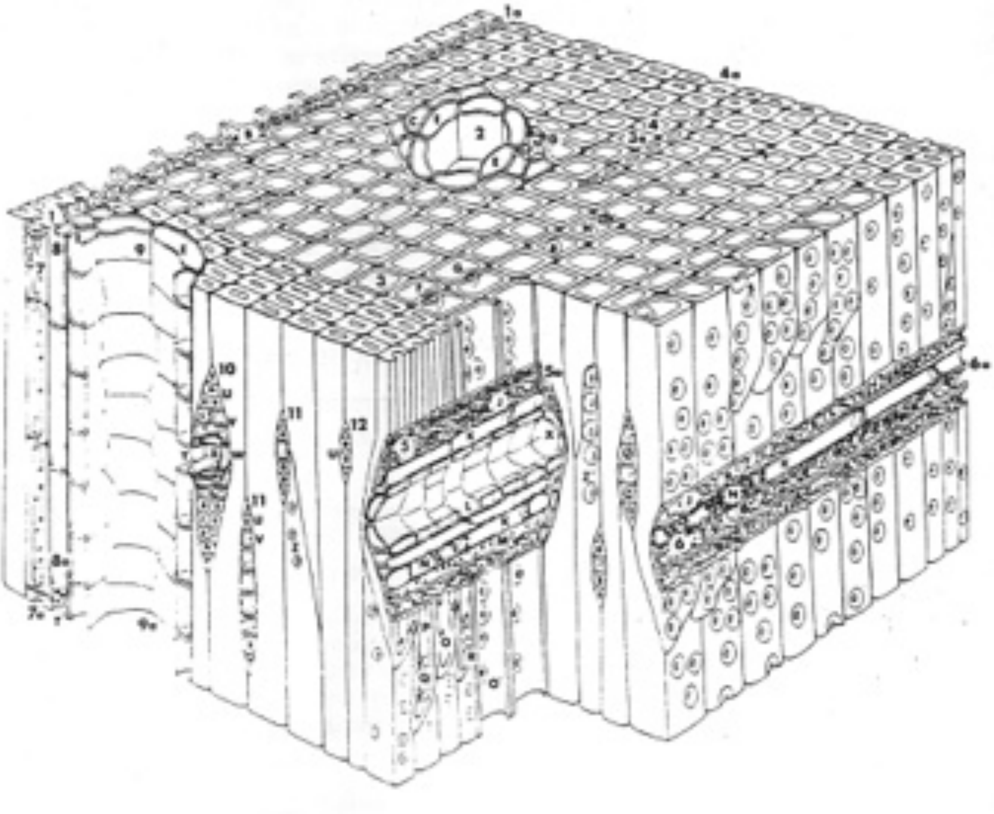
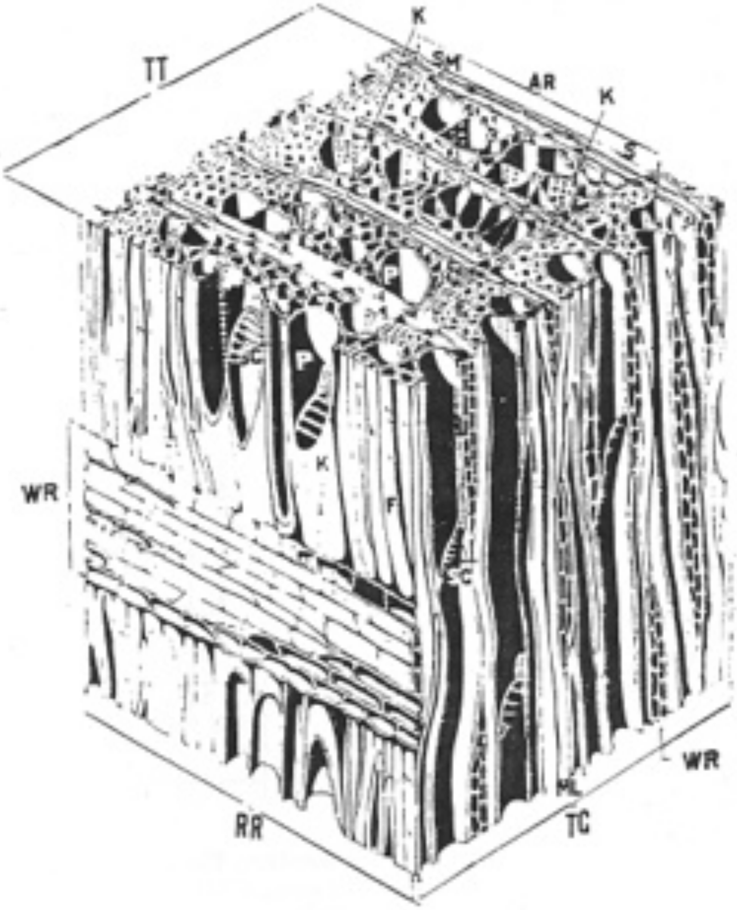


FIGURE 3.5 Variation of methane and hydrogen concentration at equilibrium (a) with temperature at a pressure of 1.0 atm, and (b) with pressure at a temperature of 800°C.

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

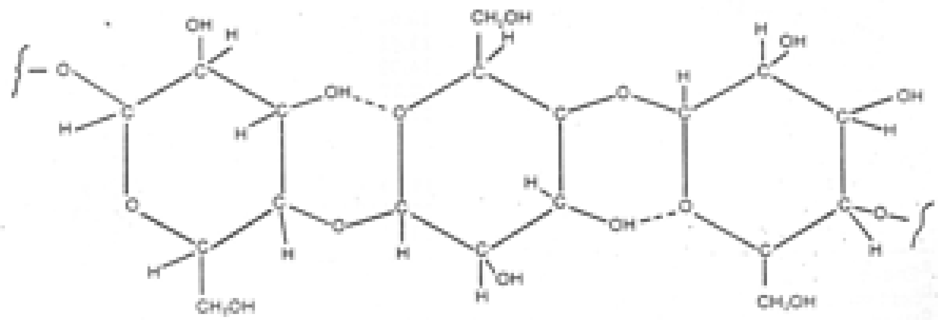


Gross Structure of a Typical Southern Pine Softwood

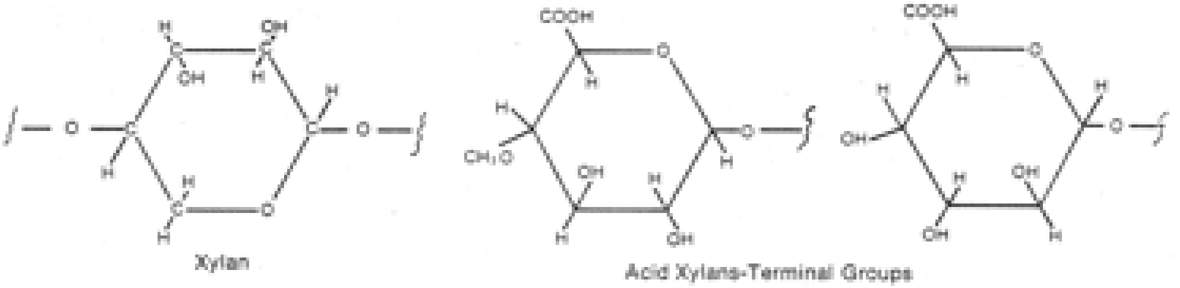


Gross Structure of a Typical Hardwood

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



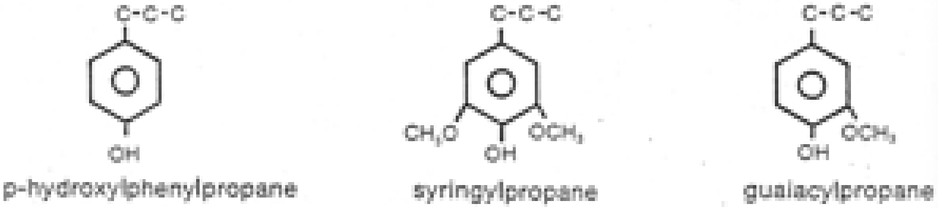
The Cellulose Molecule



Xylan

Acid Xylans-Terminal Groups

Xylan Hemicellulose Structures

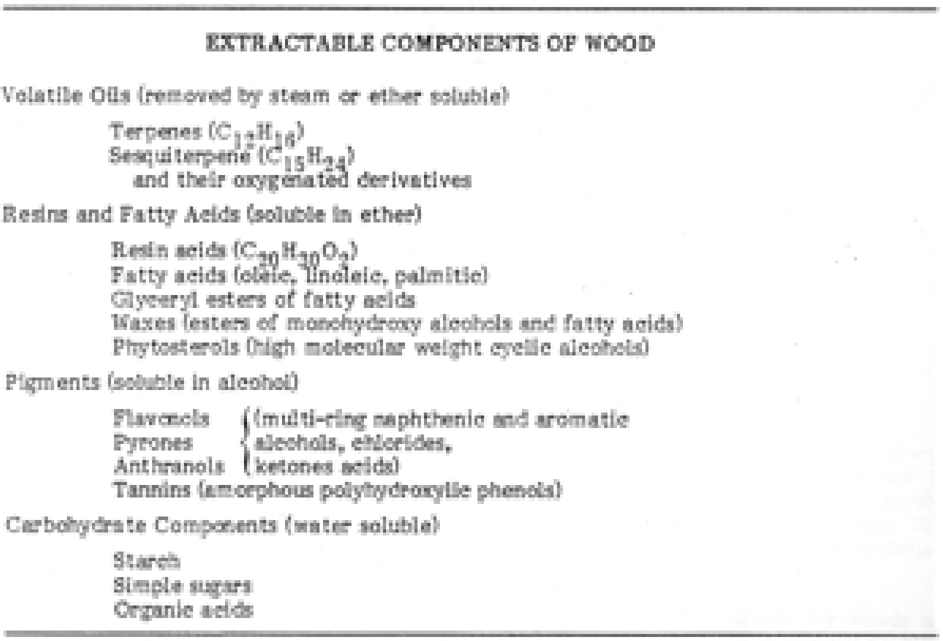


p-hydroxylphenylpropane

syringylpropane

gualacylpropane

Several Monomer Units in Lignin



EXTRACTABLE COMPONENTS OF WOOD

Volatile Oils (removed by steam or ether soluble)

Terpenes ($C_{10}H_{16}$)
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 (multi-ring naphthenic and aromatic
Pyrones alcohols, chlorides,
Anthranols 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)	25.8	59.3	14.9	Howlett and Gamache 1977
Oak (1060 F)	27.1	55.6	17.3	Howlett and Gamache 1977

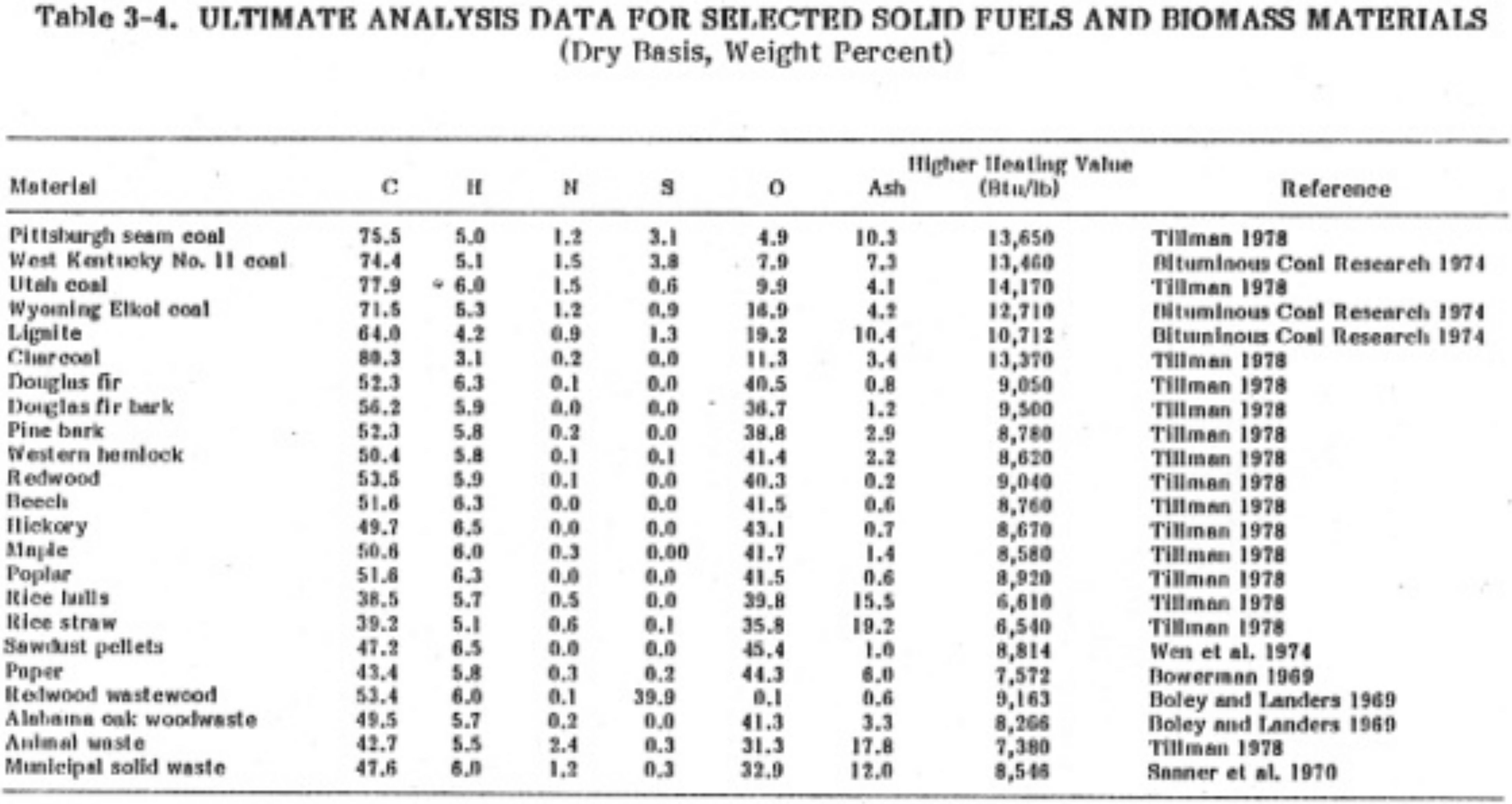
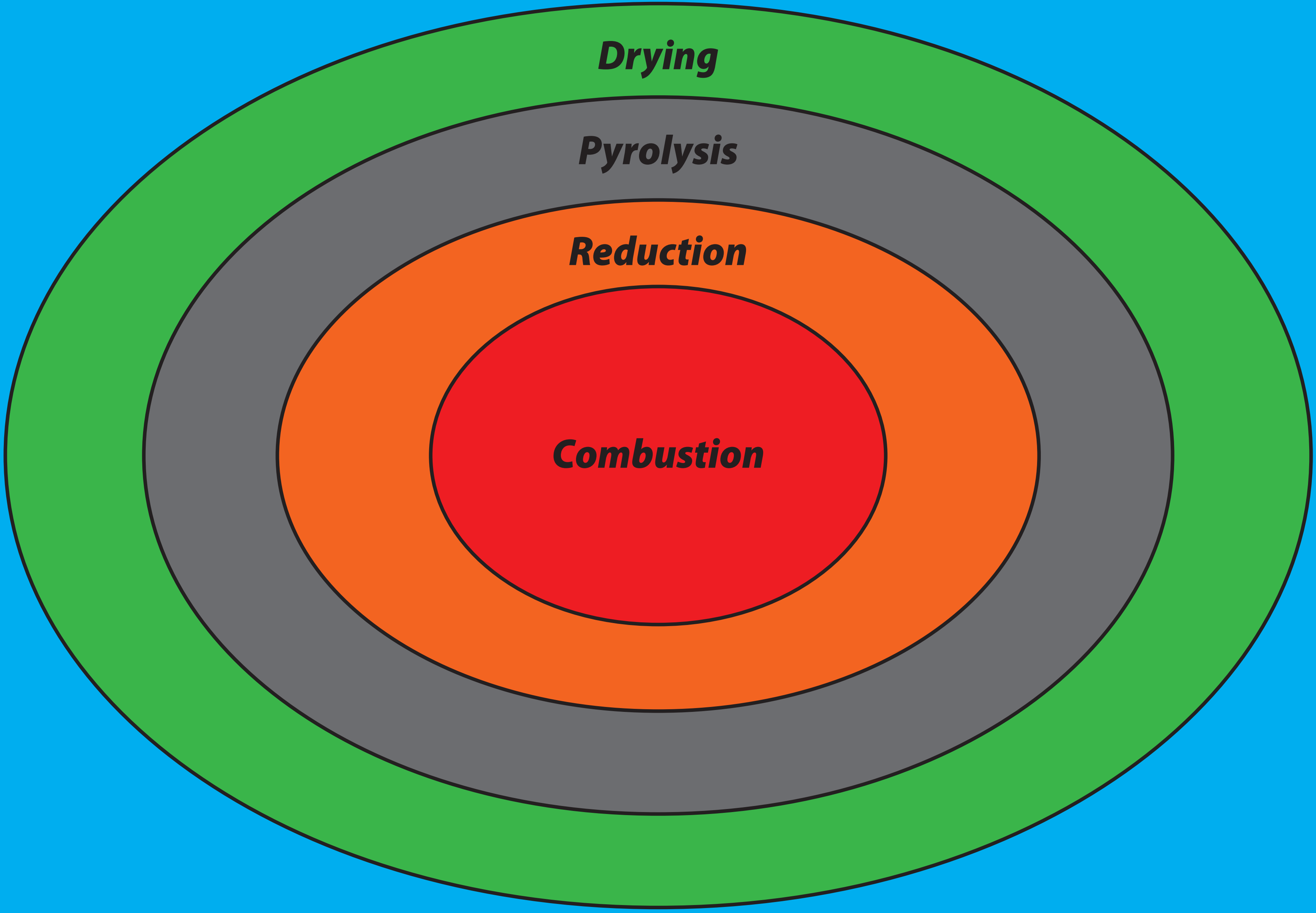


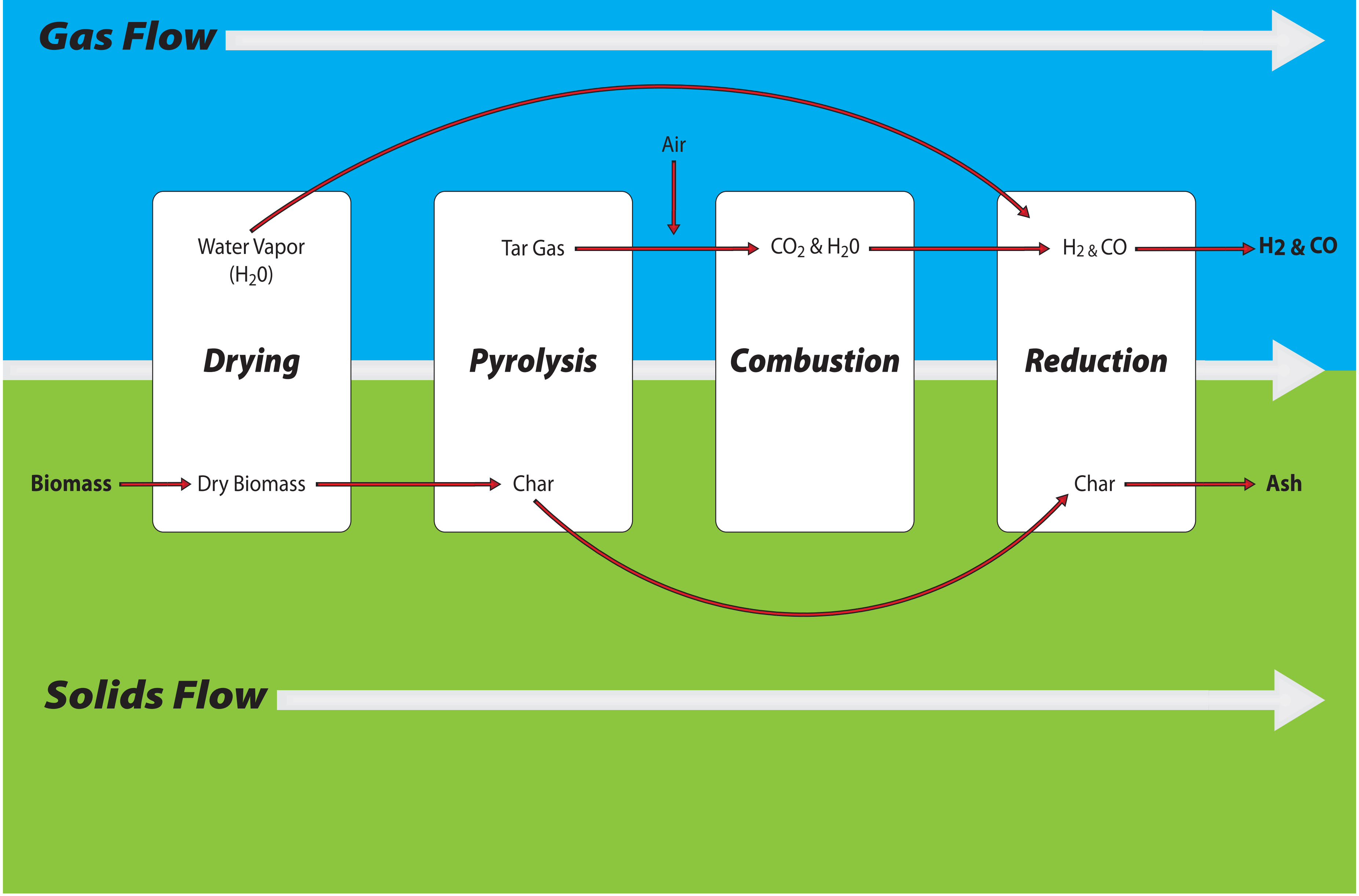
Table 3-4. ULTIMATE ANALYSIS DATA FOR SELECTED SOLID FUELS AND BIOMASS MATERIALS
(Dry Basis, Weight Percent)

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



Ideal Chemical Relationships



Gas Flow

Air

Water Vapor
(H_2O)

Drying

Tar Gas

Pyrolysis

CO_2 & H_2O

Combustion

H_2 & CO

Reduction

H2 & CO

Biomass

Dry Biomass

Char

Char

Ash

Solids Flow